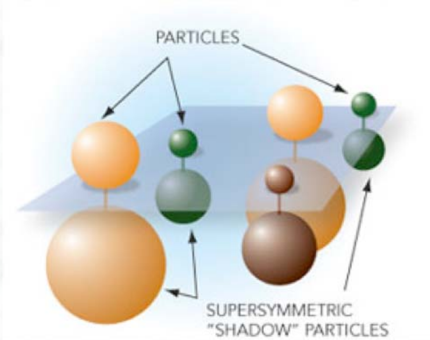
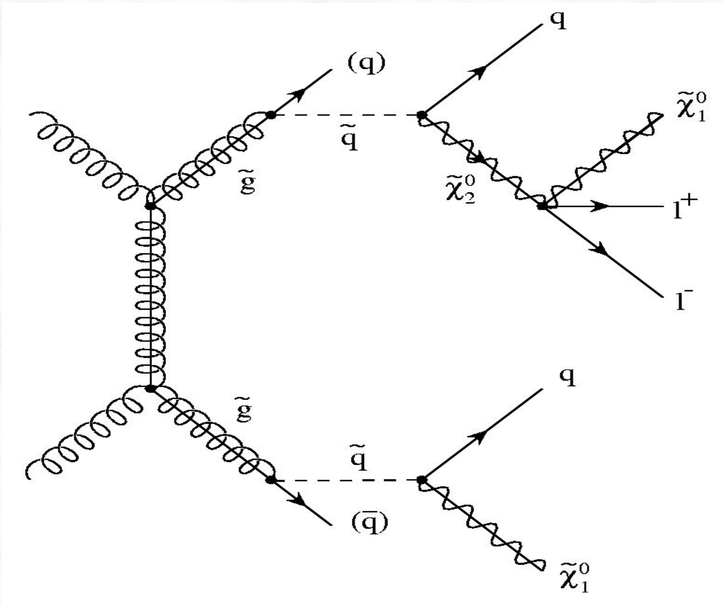
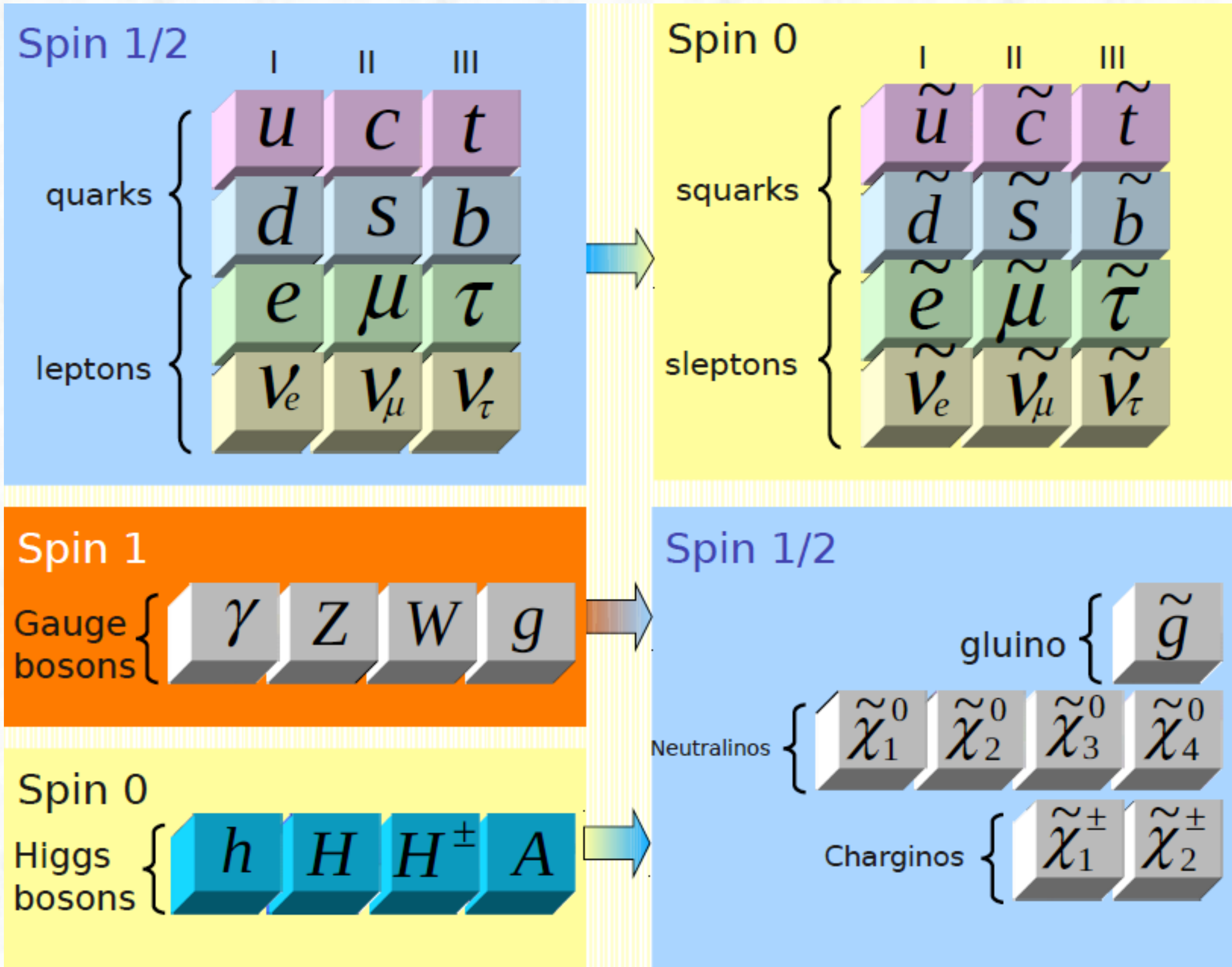
Search for Supersymmetry at the LHC





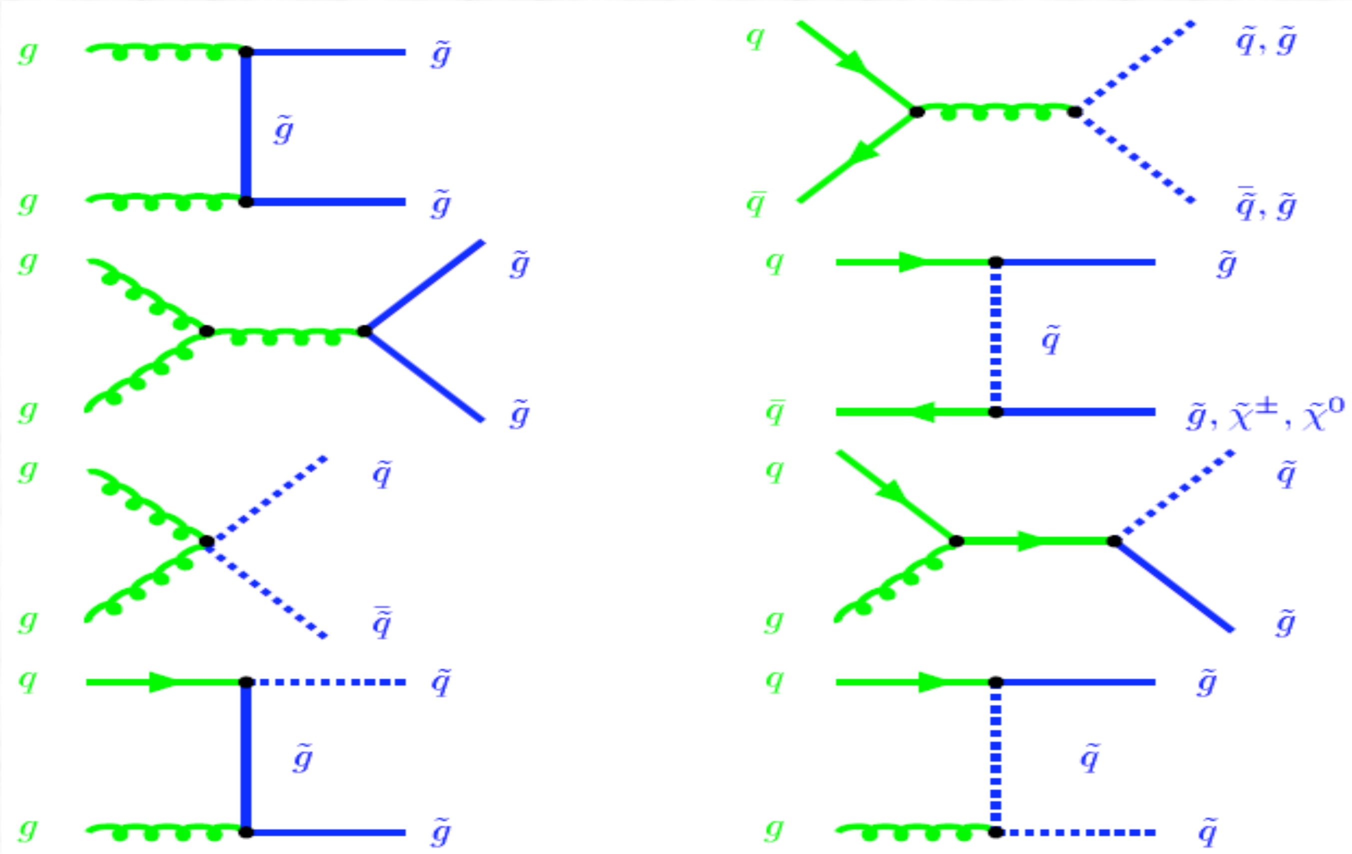
Standard Model particles　　SUSY particles



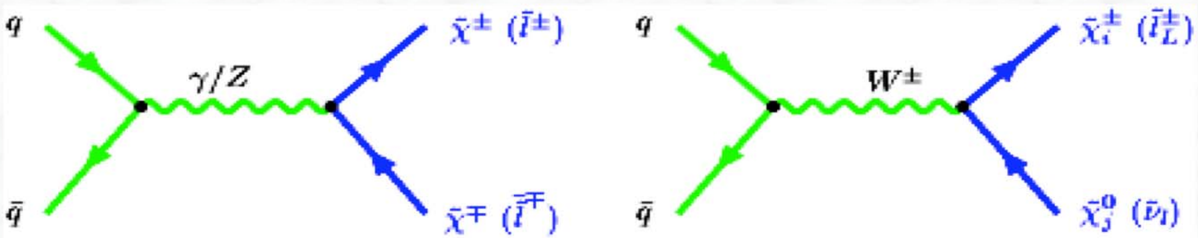
Sparticle production at the LHC

qq, qg and gg
in the initial state

→ production
of coloured SUSY
particles dominant,
via strong interaction
(α_s)

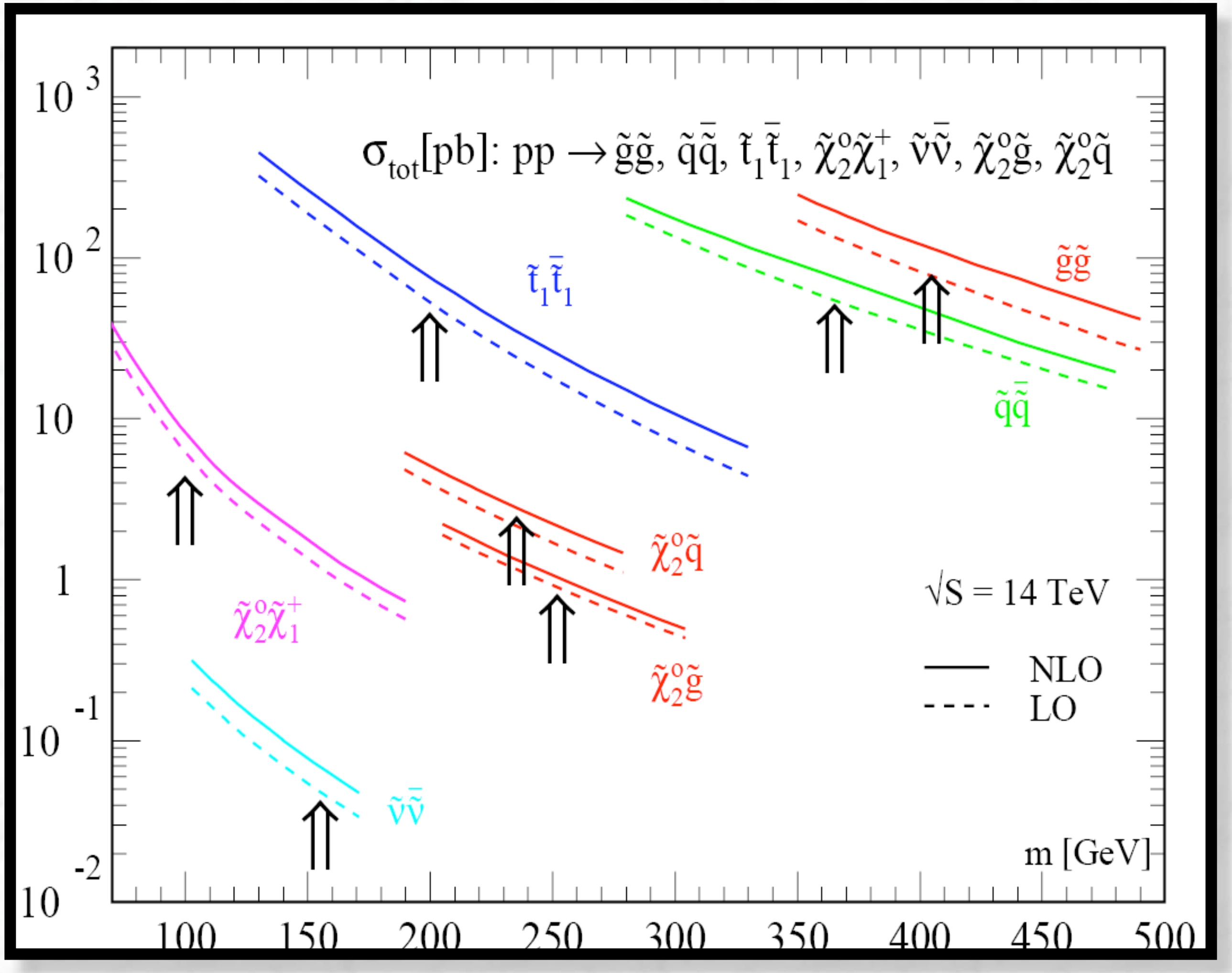


Drell-Yan production
of sleptons, charginos
and neutralinos
(lower cross sections)



Cross sections for SUSY production processes

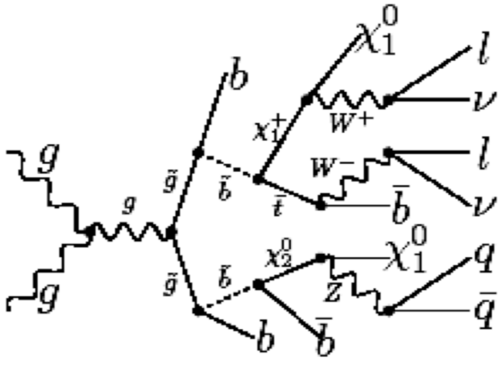
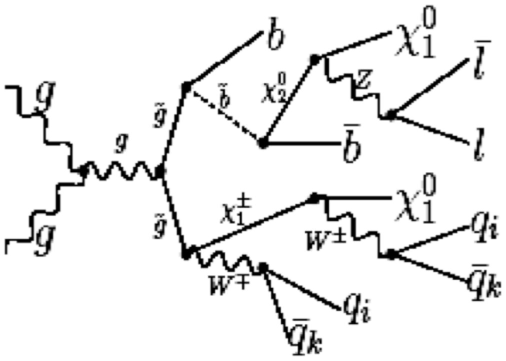
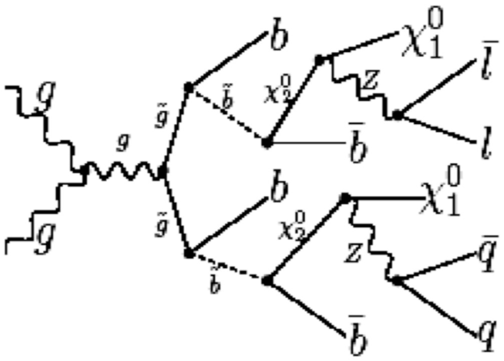
σ (pb)

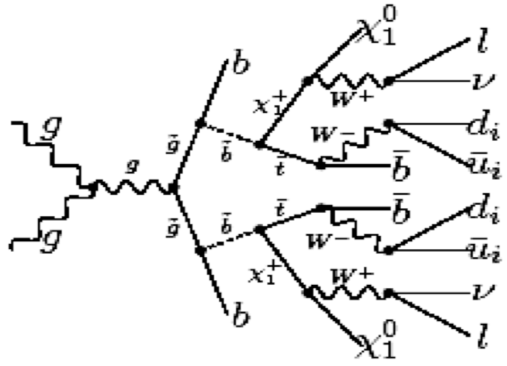
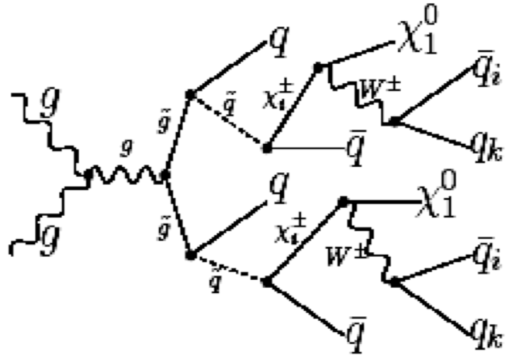
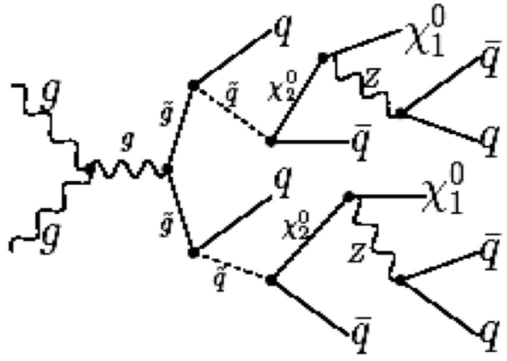


M (GeV)

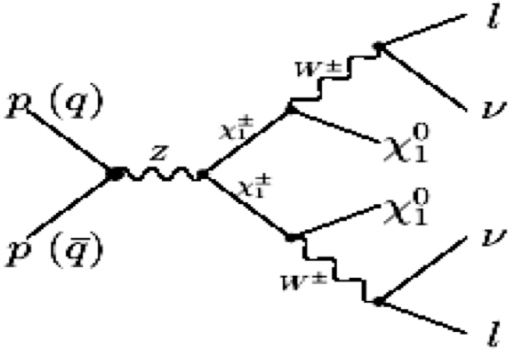
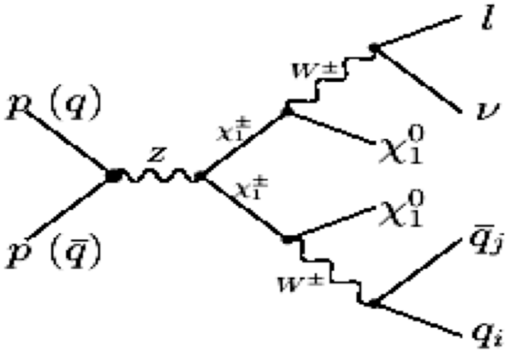
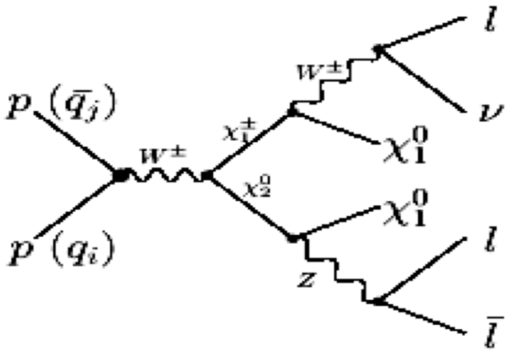
NLO corrections in QCD perturbation theory are known

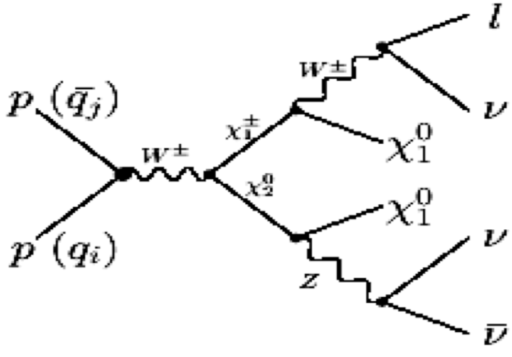
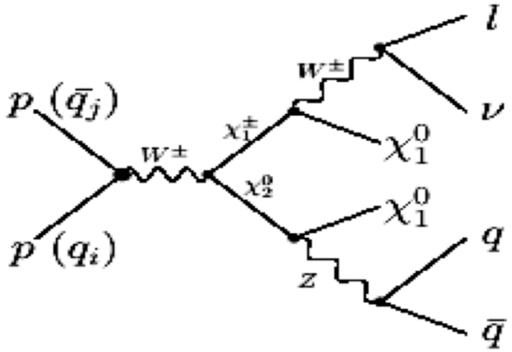
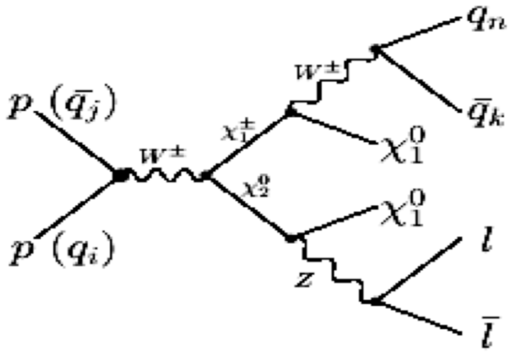
Decays of heavy SUSY particles → long and complex decay chains
Invariants in R-parity conserving SUSY: jets, E_T^{miss} (2 LSPs)

process	final states
	2ℓ 2ν $6j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$

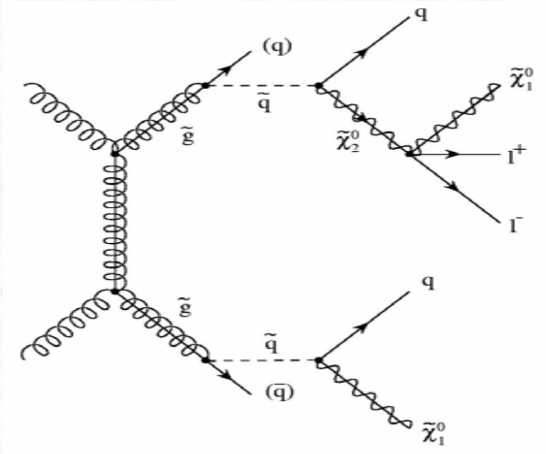
process	final states
	2ℓ 2ν $8j$ $\not{E}_T$
	$8j$ $\not{E}_T$
	$8j$ $\not{E}_T$

shorter decay chains for direct chargino / neutralino production

process	final states
	2ℓ 2ν $\not{E}_T$
	1ℓ $2j$ ν $\not{E}_T$
	3ℓ ν $\not{E}_T$

process	final states
	ℓ 3ν $\not{E}_T$
	ℓ ν $2j$ $\not{E}_T$
	2ℓ $2j$ $\not{E}_T$

Search for Supersymmetry at the LHC



- If SUSY exists at the electroweak scale, a discovery at the LHC should be easy

- Squarks and Gluinos are strongly produced

  They decay through cascades to the lightest SUSY particle (LSP)

$\Rightarrow$ combination of
Jets, Leptons, E_T^{miss}

1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

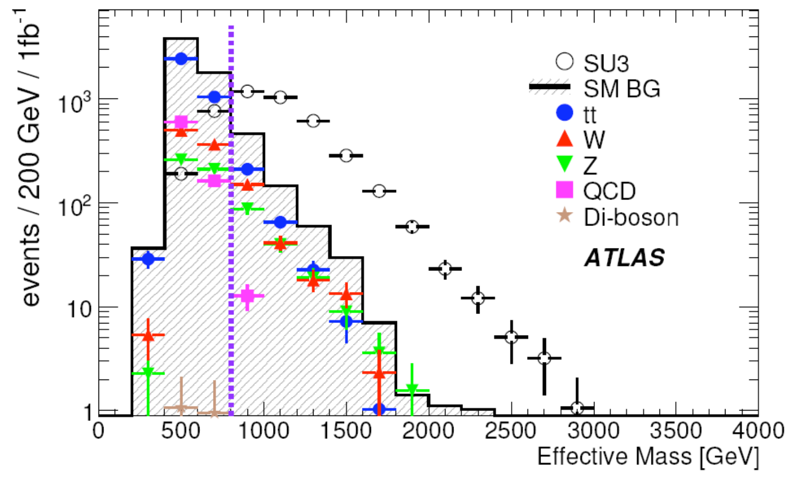
2. Step: Establish the SUSY mass scale use inclusive variables, e.g. effective mass distribution

3. Step: Determine model parameters (difficult)
   Strategy: select particular decay chains and use kinematics to determine mass combinations

A typical search for squark and gluino production

- If R-parity conserved, cascade decays produce distinctive events:
  multiple jets, leptons, and E_T^{miss}
- Typical selection: $N_{jet} > 4$, $E_T > 100, 50, 50, 50$ GeV, $E_T^{miss} > 100$ GeV
- Define: $M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$ (effective mass)

MC simulation



example: mSUGRA, point SU3 (bulk region)
m_0 = 100 GeV, $m_{1/2}$ = 300 GeV
tan β = 6, A_0 = -300 GeV, $\mu > 0$

Expectations from simulations:

LHC reach for squark- and gluino masses:

0.1 fb^{-1}	$\Rightarrow$	M ~ 750 GeV
1 fb^{-1}	$\Rightarrow$	M ~ 1350 GeV
10 fb^{-1}	$\Rightarrow$	M ~ 1800 GeV

Deviations from the Standard Model due to SUSY at the TeV scale can be detected fast !

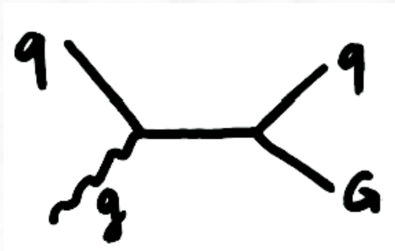
Strategy in SUSY Searches at the LHC:

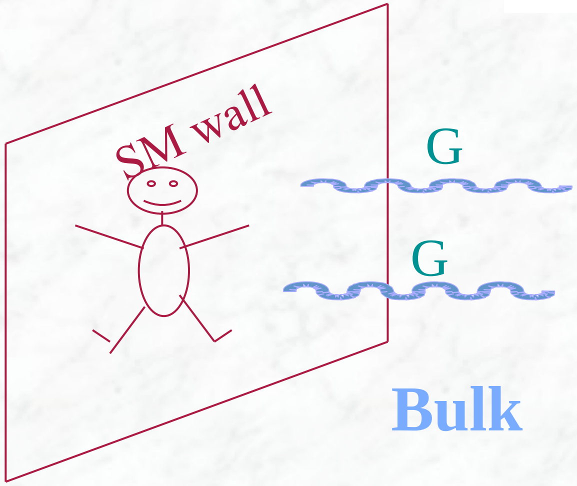
- Search for multijet + E_T^{miss} excess
- Look for special features (γ's , long lived sleptons)
- Look for $\ell^{\pm}$, $\ell^{+}\ \ell^{-}$, $\ell^{\pm}\ \ell^{\pm}$, b-jets, τ's
- End point analyses, global fit $\rightarrow$ SUSY model parameters

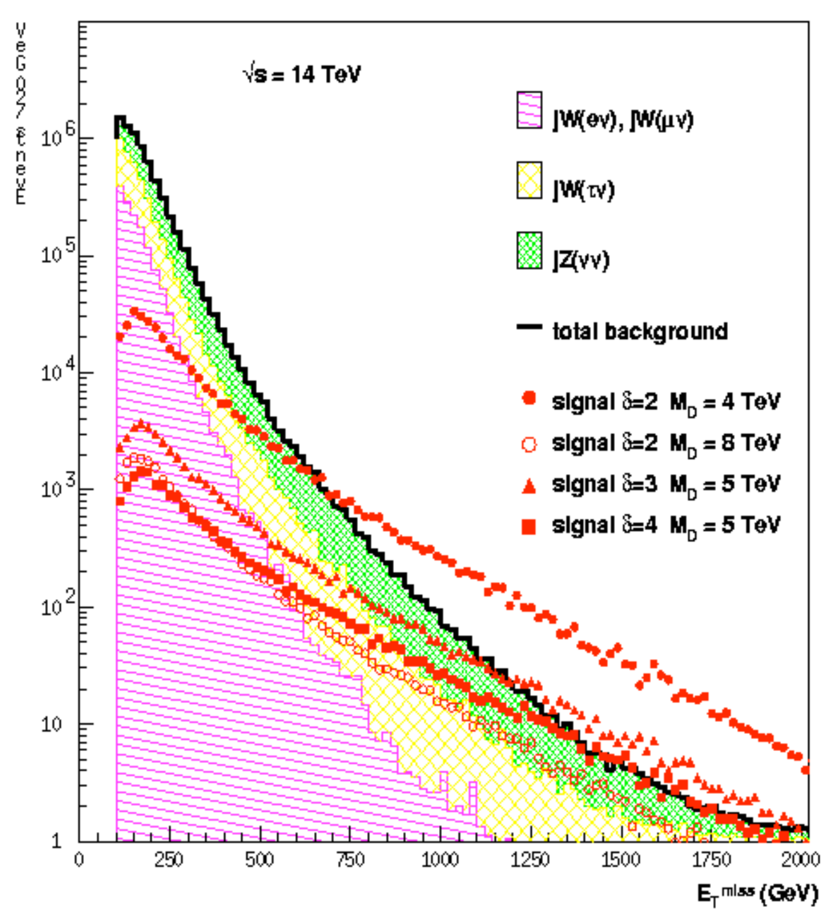
How can the parameter of the SUSY model be constrained ?

- Not easy !!
- Other possible scenarios for Physics Beyond the Standard Model could lead to similar final state signatures
  e.g. search for direct graviton production in extra dimension models

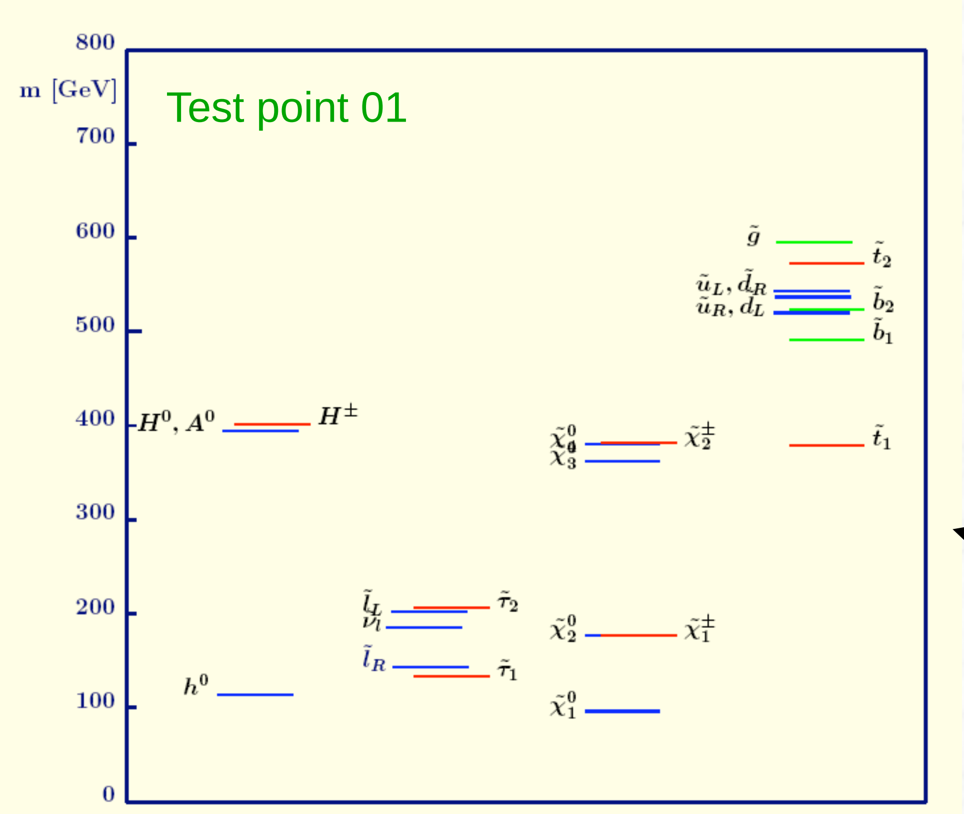
$$gg \rightarrow gG,\ qg \rightarrow qG,\ q\bar{q} \rightarrow Gg$$
$$q\bar{q} \rightarrow G\gamma$$

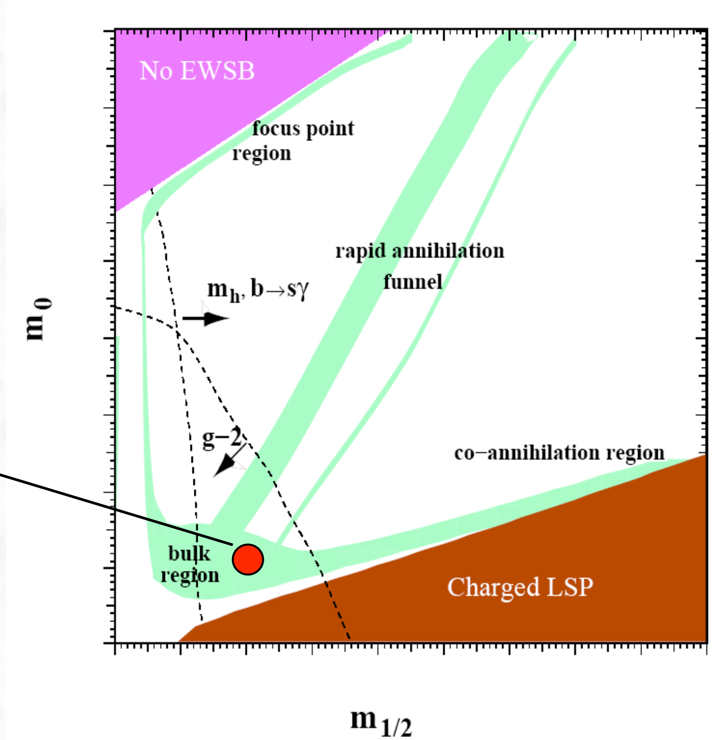






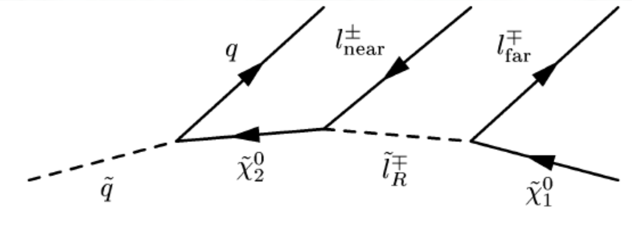
Measurement of the SUSY spectrum → Parameter of the theory





<u>LHC Strategy</u>: End point spectra of cascade decays

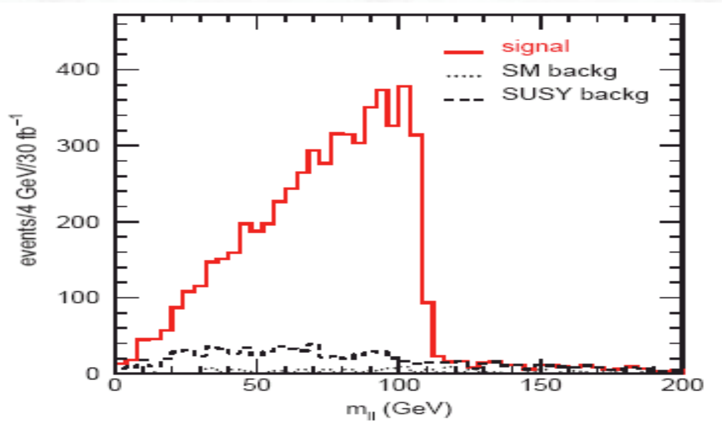
Example: $\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\ell}^{\pm}\ell^{\mp} \to q\ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$



$$M_{\ell^+\ell^-}^{max} = \frac{\sqrt{(m^2_{\chi_2^0} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\chi_1^0})}}{m_{\tilde{\ell}}}$$

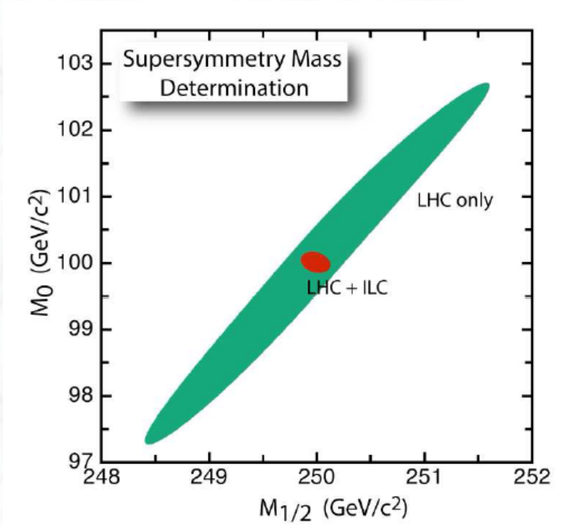
$$M_{\ell_1 q}^{max} = \frac{\sqrt{(m^2_{\chi_2^0} - m^2_{\tilde{\ell}})(m^2_{\tilde{q}} - m^2_{\chi_2^0})}}{m_{\chi_2^0}}$$

Results for point 01:



	LHC	LHC⊕ILC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (input)
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (input)
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.08
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	11.8	10.9
$\Delta m_{\tilde{g}}$	8.0	6.4
$\Delta m_{\tilde{b}_1}$	7.5	5.7
$\Delta m_{\tilde{b}_2}$	7.9	6.2
$\Delta m_{\tilde{l}_L}$	5.0	0.2 (input)
$\Delta m_{\tilde{\chi}_4^0}$	5.1	2.23

L = 300 fb^{-1}



What do the LHC data say ?

Search channels (R parity violation):

- E_T^{miss} + multijets + 0 lepton
- E_T^{miss} + multijets + 1 lepton
- E_T^{miss} + b-jets + 0/1 lepton
- E_T^{miss} + leptons
- E_T^{miss} + photons
- …….

Some useful variable for SUSY searches at the LHC

- E_T^{miss} : missing transverse energy,
  (measured from the energy depositions in the calorimeters and from muons)

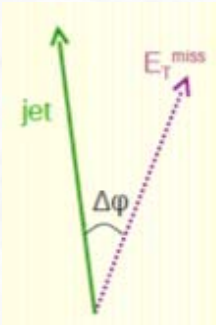
- M_{eff} : effective mass,
  scalar sum of transverse energies of selected high p_T objects, including leptons and E_T^{miss}

- H_T : scalar sum of total transverse energy in selected jets (hadronic activity)
- H_T^{miss} : modulus of vector sum of selected jets

- m_T : transverse mass (in general: m_T (lepton, E_T^{miss}))

$$m_T = \sqrt{2 p_T^e E_T^{miss} (1 - \cos \Delta\phi(e, p_T^{miss})}$$

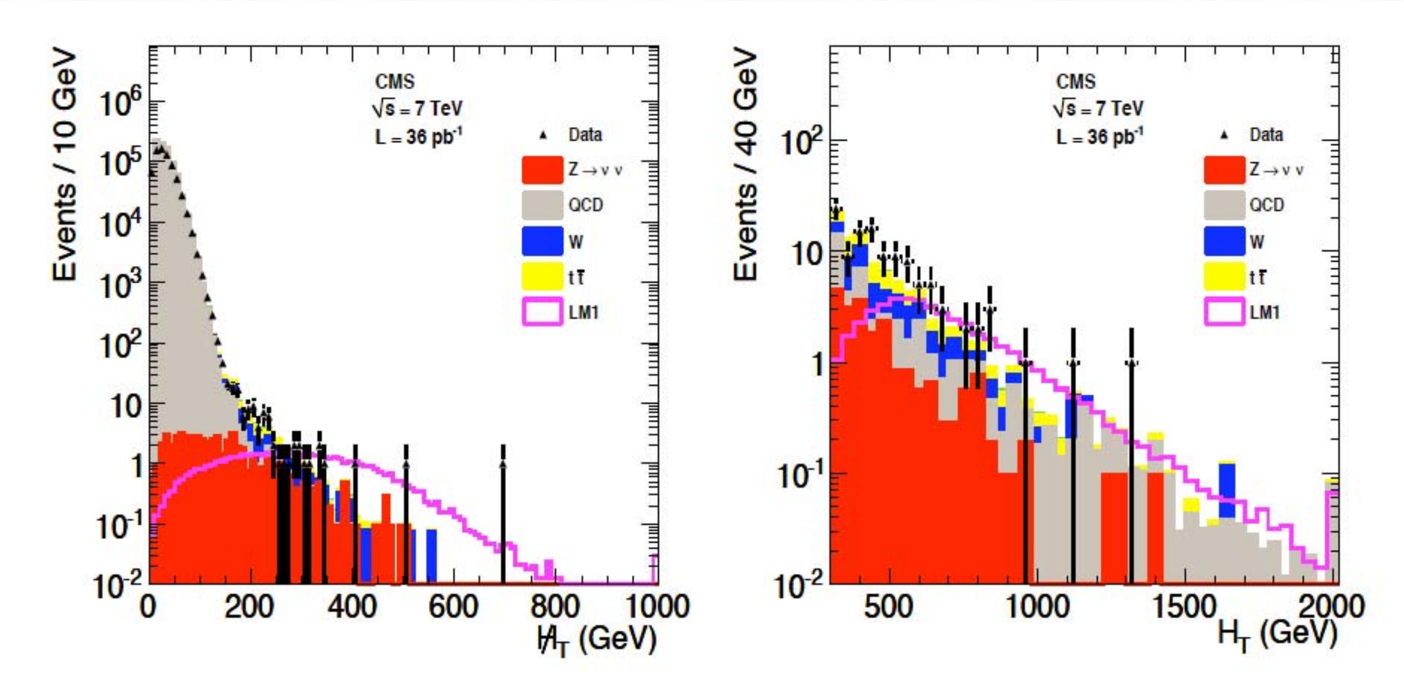
- $\Delta\phi$ (jet, E_T^{miss}): angle between the missing transverse energy vector and a jet in the transverse plane
  important to reject “fake” background from QCD jet production



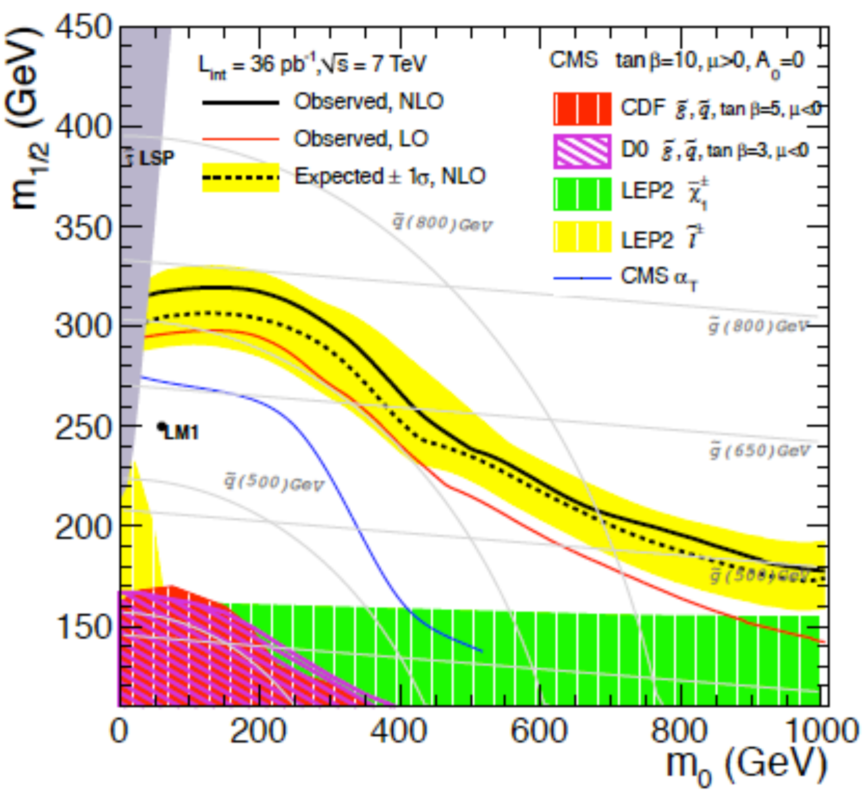
First results on the search for Etmiss + jets, no leptons (2010 data)

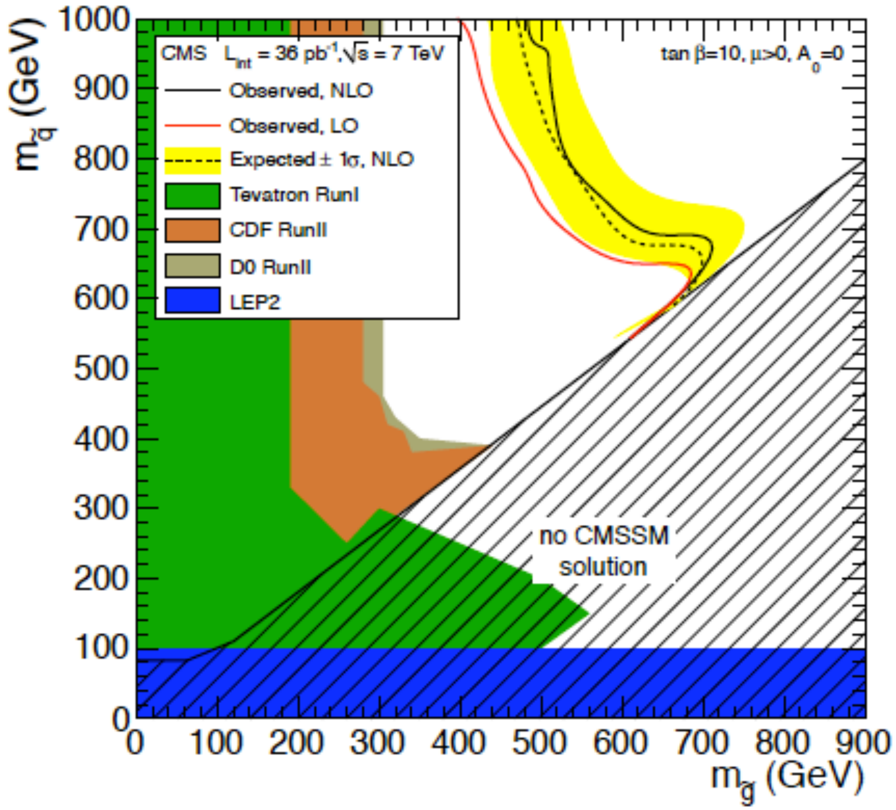
Simple selection:

- 3 jets with $p_T > 50$ GeV, $|\eta| < 2.5$
- $H_T > 300$ GeV (scalar sum of jets with $p_T > 50$ and $|\eta| < 2.5$)
- $H_T^{miss} > 150$ GeV (modulus of vector sum of jets with $p_T > 30$ GeV and $|\eta| < 5$)



- Good agreement between data and expectations from Standard Model processes
- No evidence for an excess → limits in SUSY parameter space





- Significant extension of exclusion contours in the squark-gluino mass plane
- m_{gluino} below 500 GeV excluded for m_{squark} < 1000 GeV

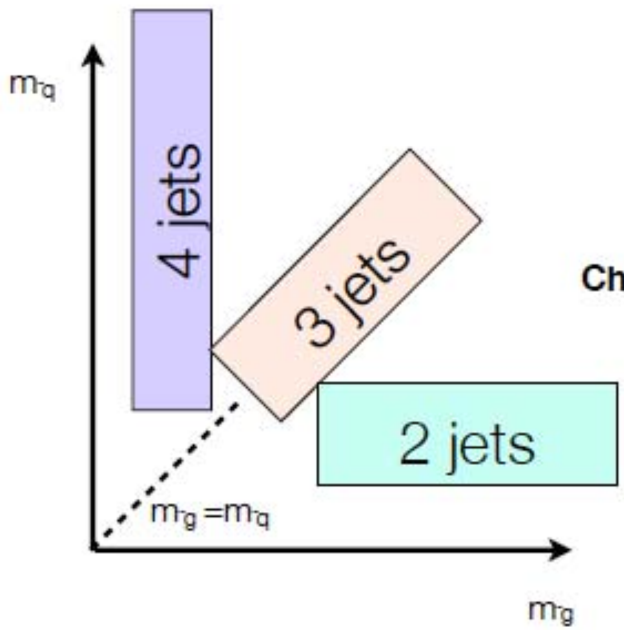
First results on the search for E_T^{miss} + jets (1.04 fb^{-1})

(large part of 2011 data already included)

Selection of events with E_T^{miss} + jets

Split the analysis according to jet multiplicities: 2, 3 and 4 jets
(different sensitivity for different squark/gluino mass combinations,
i.e. in different regions of SUSY parameter space)

Definition of signal regions:



	Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets	High mass
Trigger requirements	E_T^{miss}	> 130	> 130	> 130	> 130
	Leading jet p_T	> 130	> 130	> 130	> 130
Channel definition	Second jet p_T	> 40	> 40	> 40	> 80
	Third jet p_T	–	> 40	> 40	> 80
	Fourth jet p_T	–	–	> 40	> 80
Reduce QCD	$\Delta\phi(\text{jet}, E_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
	E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
Enhance signal	m_{eff} [GeV]	> 1000	> 1000	> 500/1000	> 1100

$$m_{eff} = \sum_{i=1}^{n} |\vec{p}_T^{\,jet\ i}| + E_T^{miss}$$

- Three different analyses, depending on squark / gluinos mass relations:

  (i) dijet analysis
  small m_0, m(squark) < m(gluino)

  $$\tilde{q}\bar{\tilde{q}} \to q\tilde{\chi}_1^0\bar{q}\tilde{\chi}_1^0$$

  (ii) 3-jet analysis
  intermediate m_0 m(squark) ≈ m(gluino)

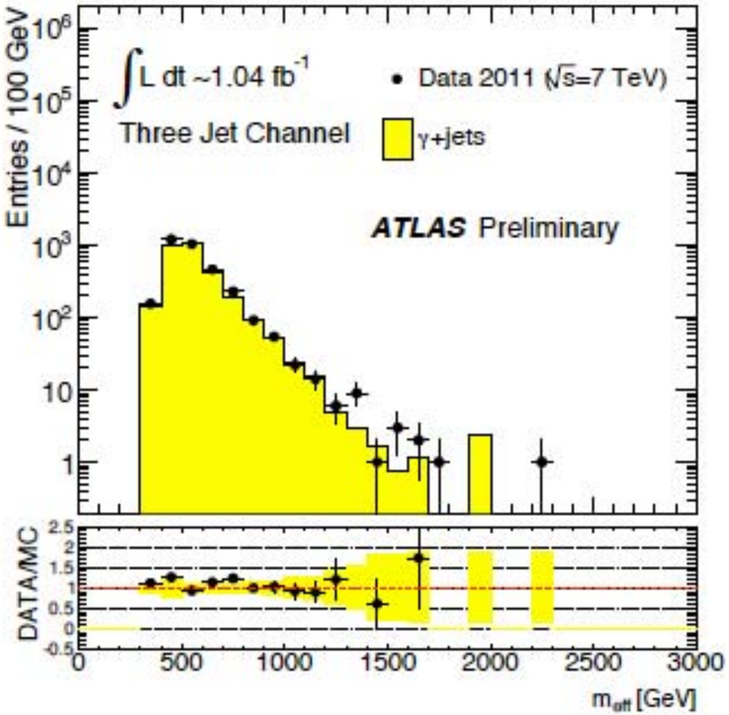
  $$\tilde{q}\tilde{g} \to q\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$$

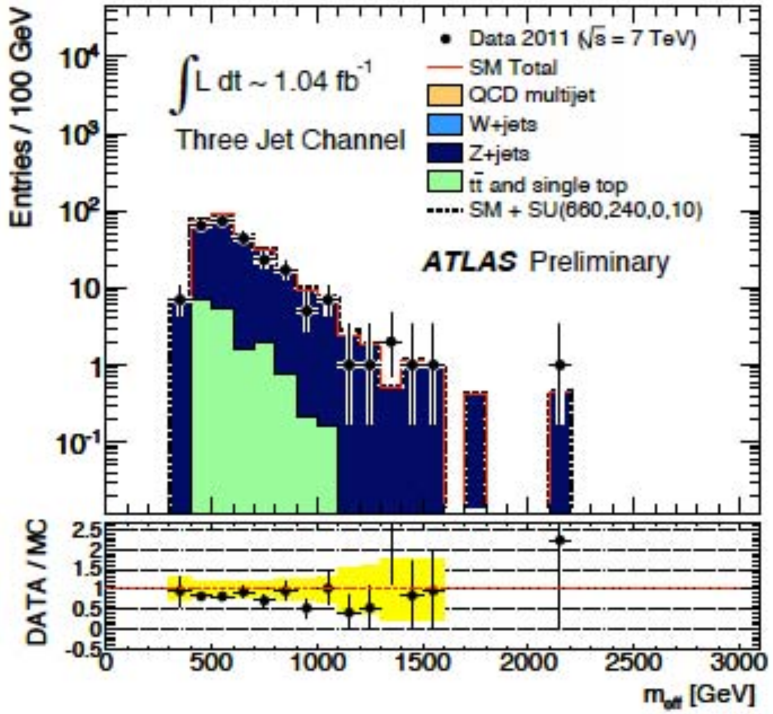
  (iii) Gluino analysis
  large m_0, m(squark) > m(gluino)

  $$\tilde{g}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$$

Z control region

- $Z \rightarrow \nu\nu$ is the dominant component of the total Z background
- Estimation done in 2 CR (in both cases replacing the boson with MET):
  - γ+jets events (use robustness of ratio between photon and Z production cross section)
  - Z ($\rightarrow$ee,μμ) + jets



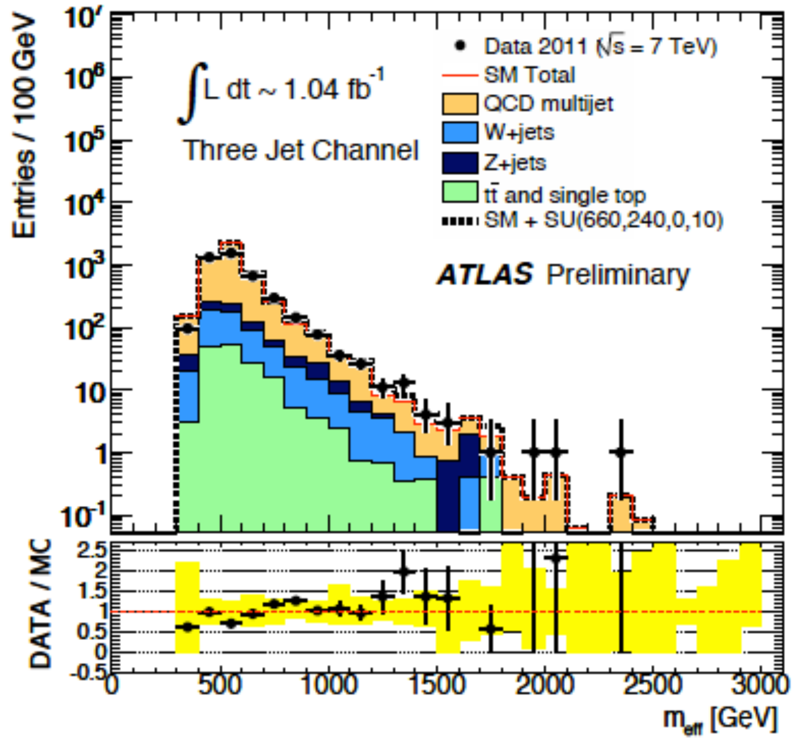


Estimation of QCD background:

- Select event in data where $\Delta \phi$ (jet, E_T^{miss}) < 0.4

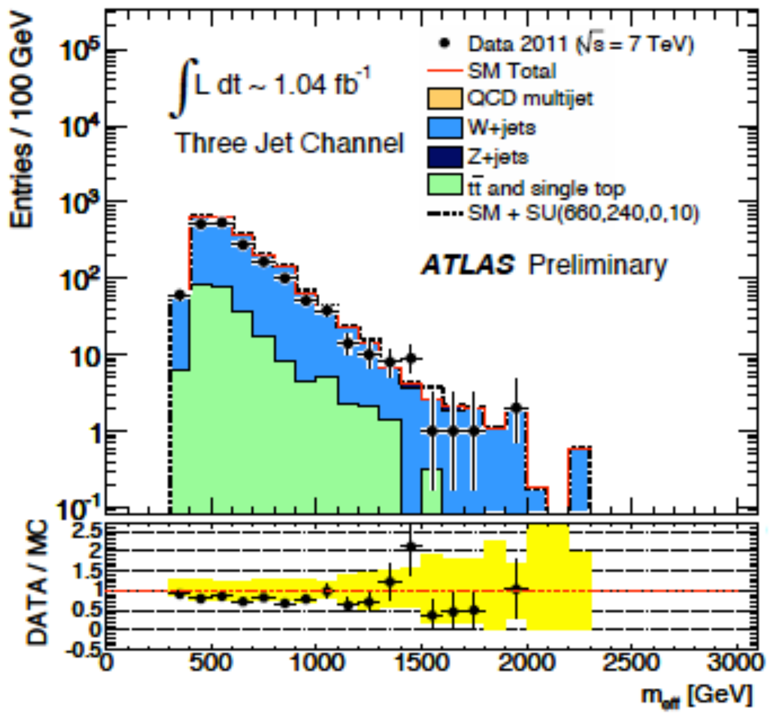
- QCD multijet events have large E_T^{miss} due to mismeasurments of jet or due to heavy flavour decays in jets;

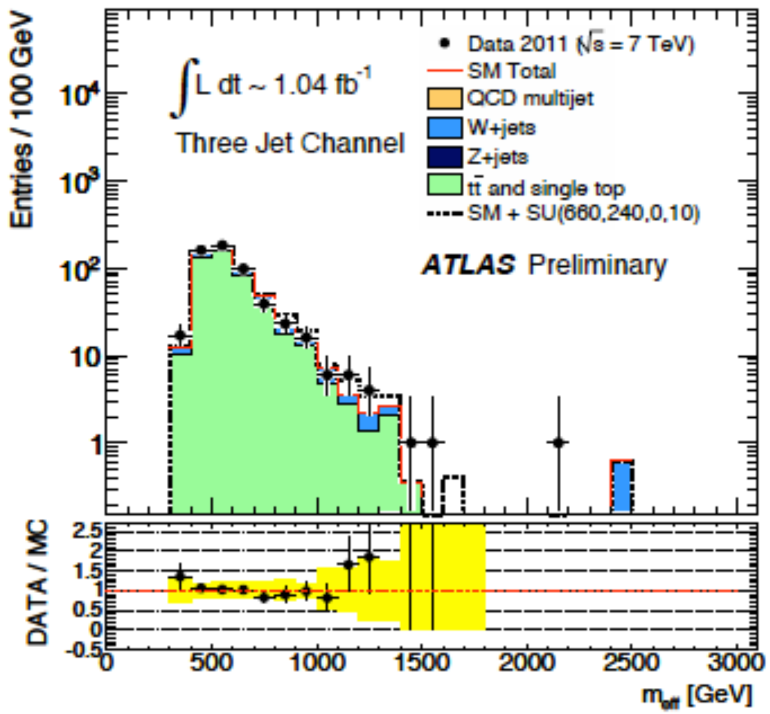
  In both cases, E_T^{miss} is aligned with the jets



W and top control regions

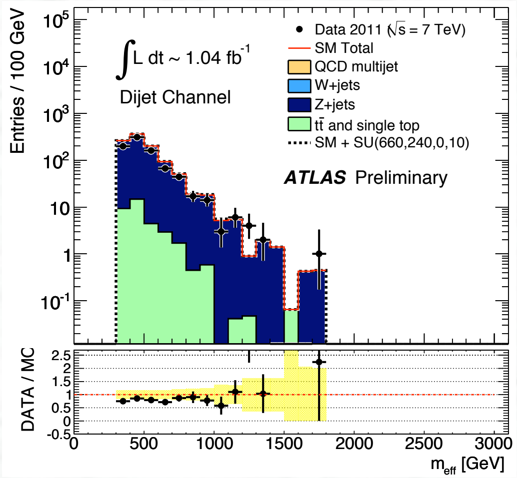
- Two control regions defined in events containing one additional lepton (additional selection 30 GeV < M_T < 100 GeV):
  - Applying a b-tag veto a W control region is obtained.
  - Applying a b-tag requirement a top control region is obtained.

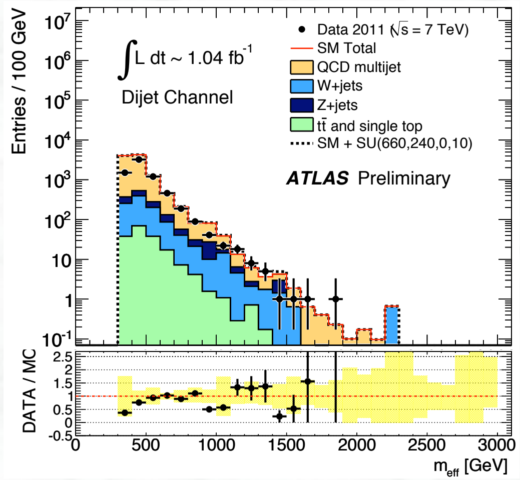




Summary on control of backgrounds using data

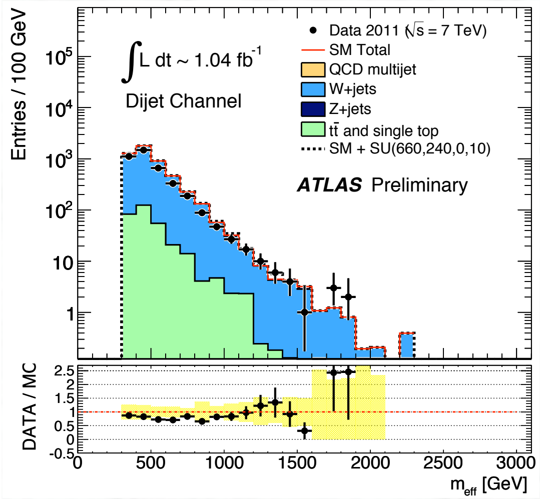
(control regions, very important !!)

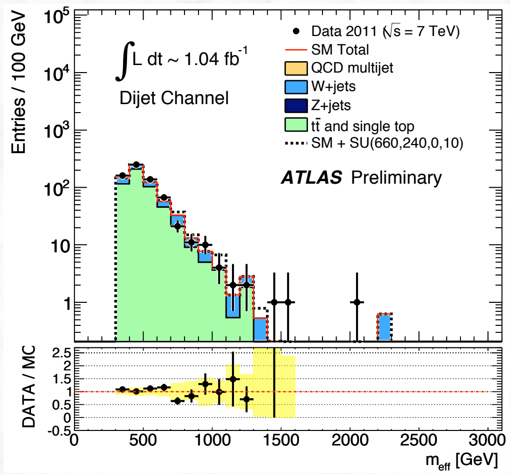




A: Z + jet events, Z → ee
(to estimate Z → $\nu\nu$ background, likewise γ + jet events were used)

B: QCD multijet background
(reverse cut on $\Delta\phi$ (jet, E_T^{miss})





C: W → lν + jet control region
(select events with one lepton,
30 < $M_T(l,E_T^{miss})$ < 100 GeV,
no b-jet to suppress top contribution)

D: top quark control region
(same selection as for W events,
but require b-tag)

First results on the search for E_T^{miss} + jets (1.04 fb^{-1})

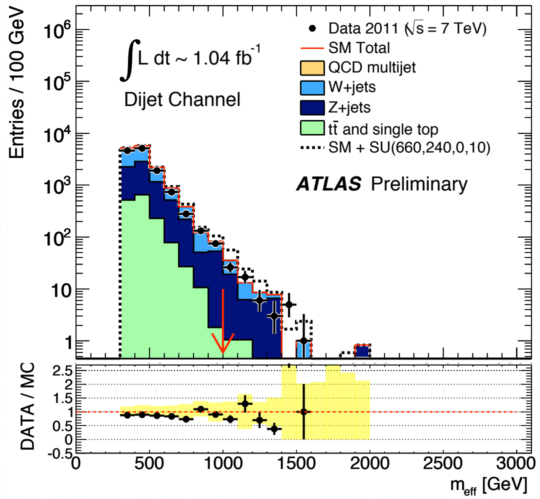
(large part of 2011 data already included)

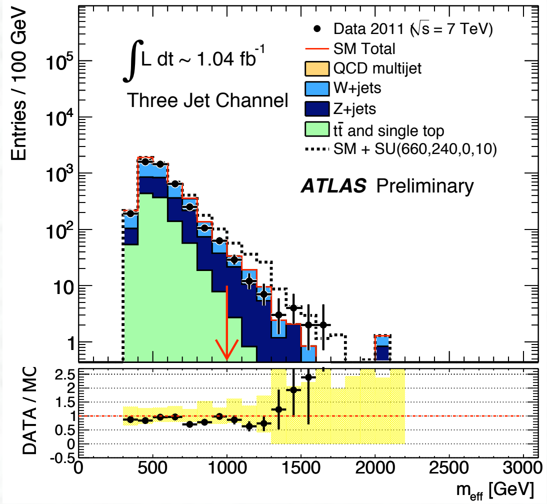
Process	Signal Region				
	≥ 2-jet	≥ 3-jet	≥ 4-jet, m_{eff} > 500 GeV	≥ 4-jet, m_{eff} > 1000 GeV	High mass
Z/γ+jets	$32.5 \pm 2.6 \pm 6.8$	$25.8 \pm 2.6 \pm 4.9$	$208 \pm 9 \pm 37$	$16.2 \pm 2.1 \pm 3.6$	$3.3 \pm 1.0 \pm 1.3$
W+jets	$26.2 \pm 3.9 \pm 6.7$	$22.7 \pm 3.5 \pm 5.8$	$367 \pm 30 \pm 126$	$12.7 \pm 2.1 \pm 4.7$	$2.2 \pm 0.9 \pm 1.2$
$t\bar{t}$+ Single Top	$3.4 \pm 1.5 \pm 1.6$	$5.6 \pm 2.0 \pm 2.2$	$375 \pm 37 \pm 74$	$3.7 \pm 1.2 \pm 2.0$	$5.6 \pm 1.7 \pm 2.1$
QCD jets	$0.22 \pm 0.06 \pm 0.24$	$0.92 \pm 0.12 \pm 0.46$	$34 \pm 2 \pm 29$	$0.74 \pm 0.14 \pm 0.51$	$2.10 \pm 0.37 \pm 0.83$
Total	$62.3 \pm 4.3 \pm 9.2$	$55 \pm 3.8 \pm 7.3$	$984 \pm 39 \pm 145$	$33.4 \pm 2.9 \pm 6.3$	$13.2 \pm 1.9 \pm 2.6$
Data	58	59	1118	40	18

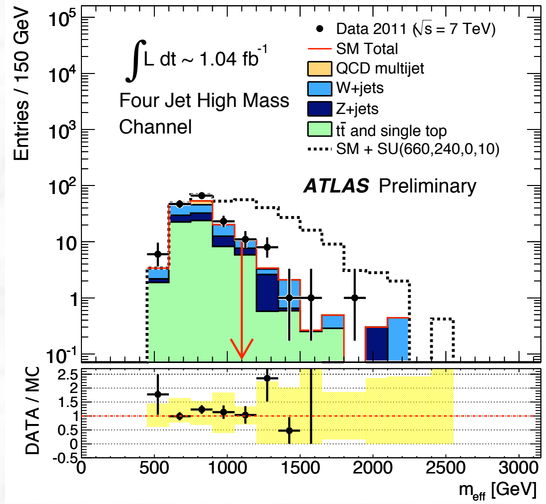
Observed and expected event numbers (from Standard Model processes)

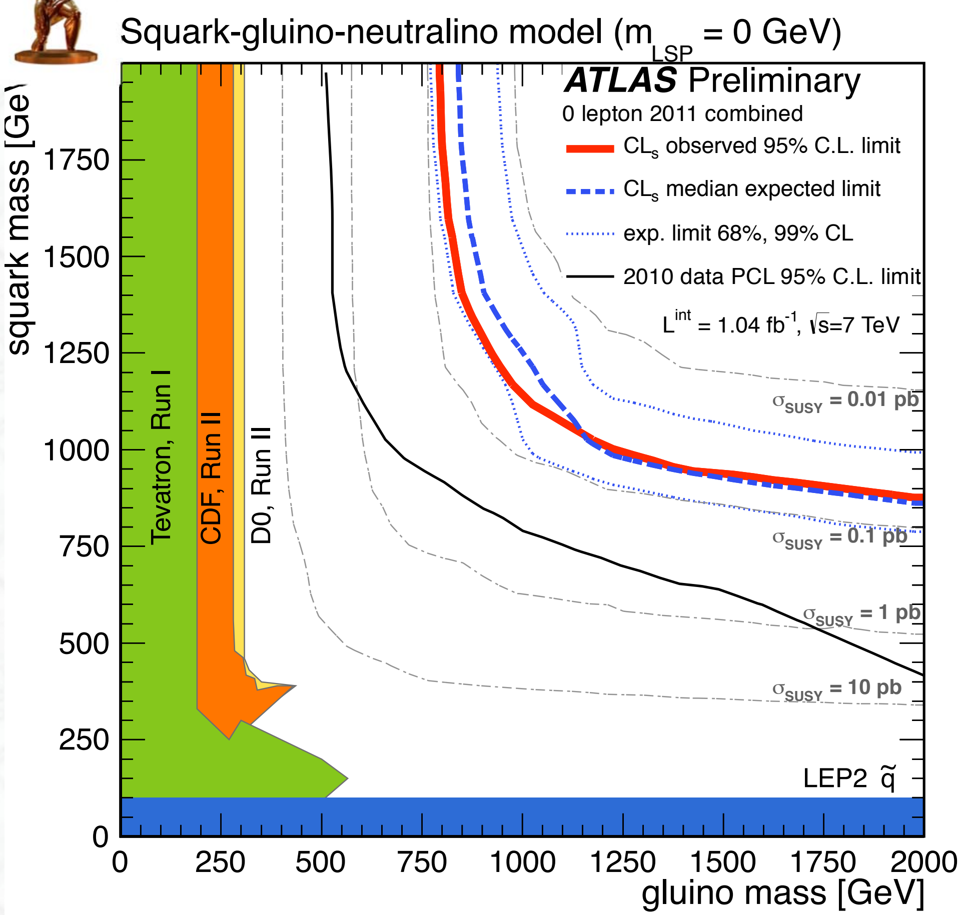
dominant backgrounds:
- W/Z + jets
- ttbar production

Normalized in control regions !
(as explained on the previous slide)







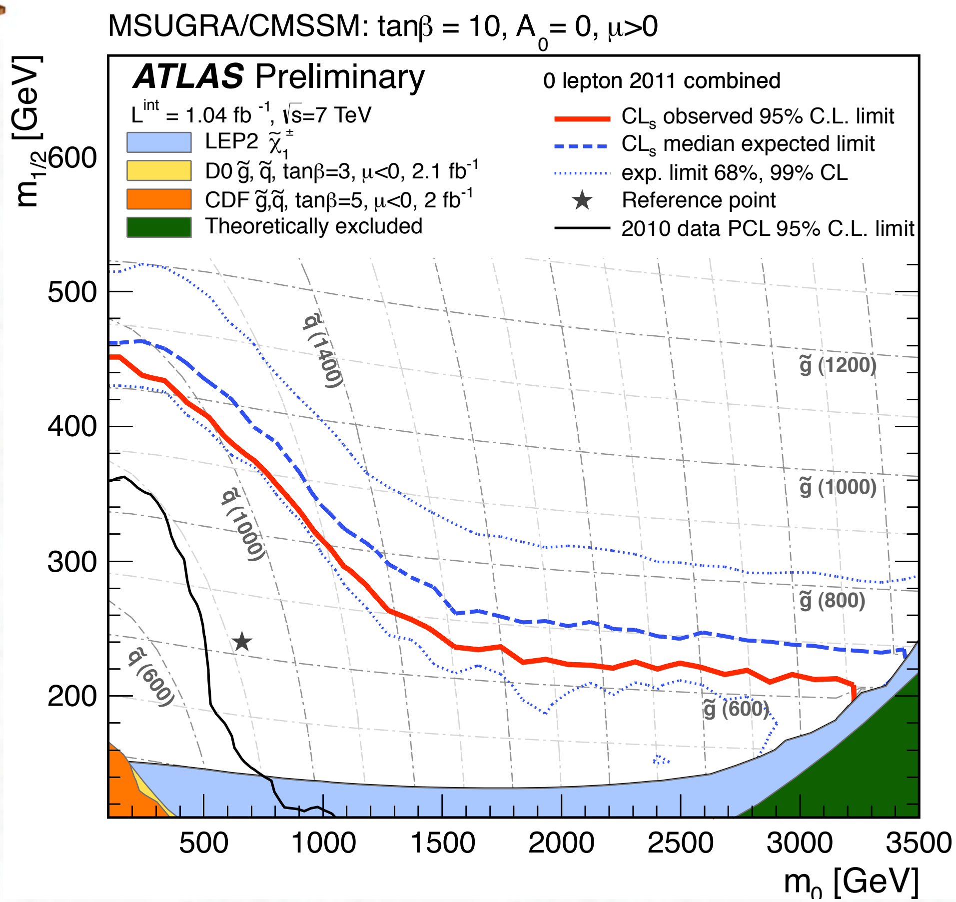


Interpretation of the results in the (m_{gluino}, m_{squark})-plane as 95% C.L. exclusion limits in a simplified SUSY model:

- $m_{\chi} = 0$
- masses of gluinos and of 1st and 2nd generation squarks as given on plot
- all other SUSY masses are assumed to be decoupled, with masses of 5 TeV

Large area of mass combinations excluded, significant improvement compared to Tevatron results and to 2010 results (black curve)

mSUGRA interpretation

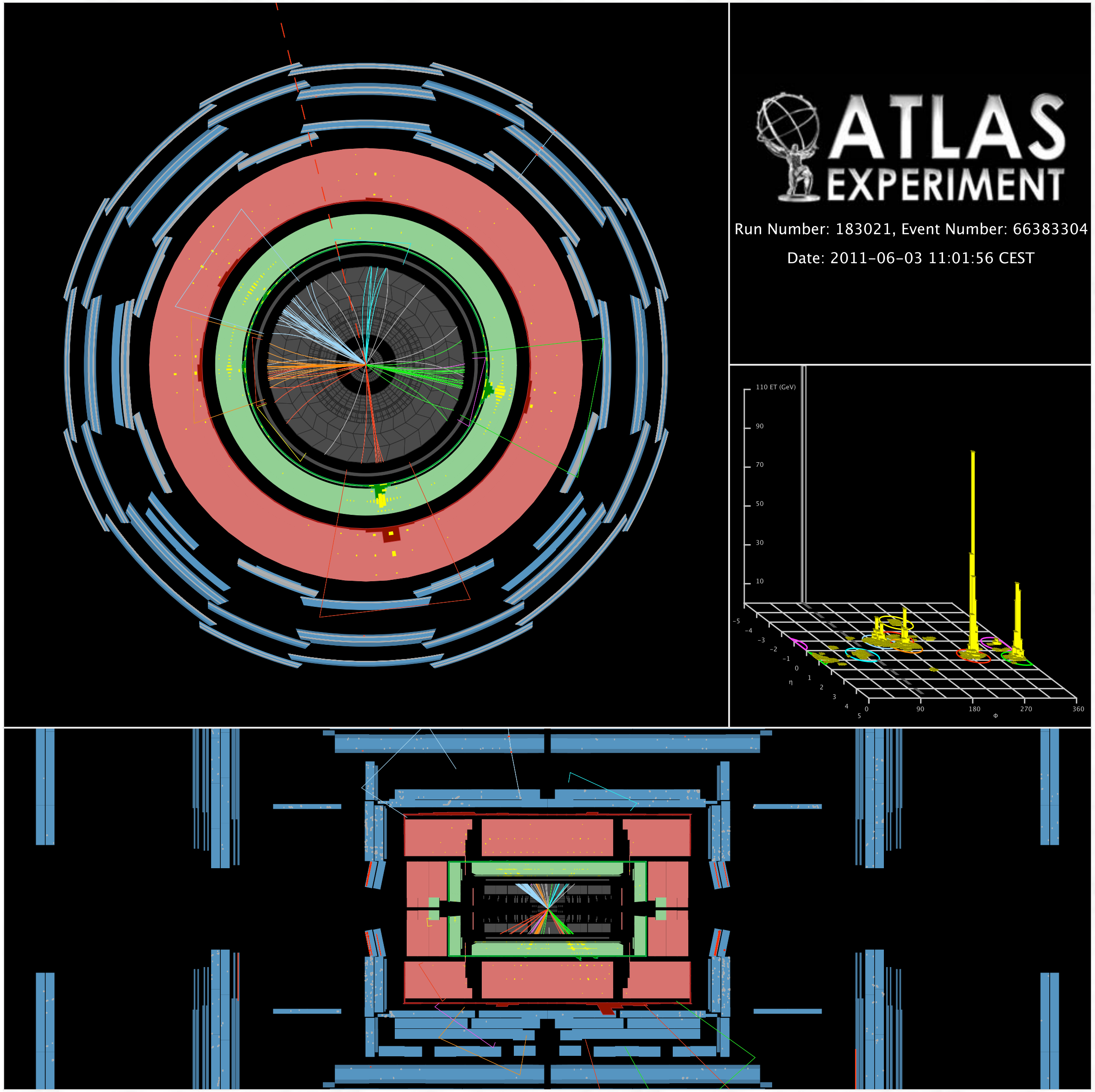


$\tan\beta = 10$, $A_0 = 0$, $\mu > 0$

The channel (2, 3, 4, jets) with the best expected limit is taken at each point in parameter space

MSSM/cMSSM interpretation (for equal squark and gluino masses):

$L = 1.04\ fb^{-1}$: m(squark), m(gluino) > 980 GeV



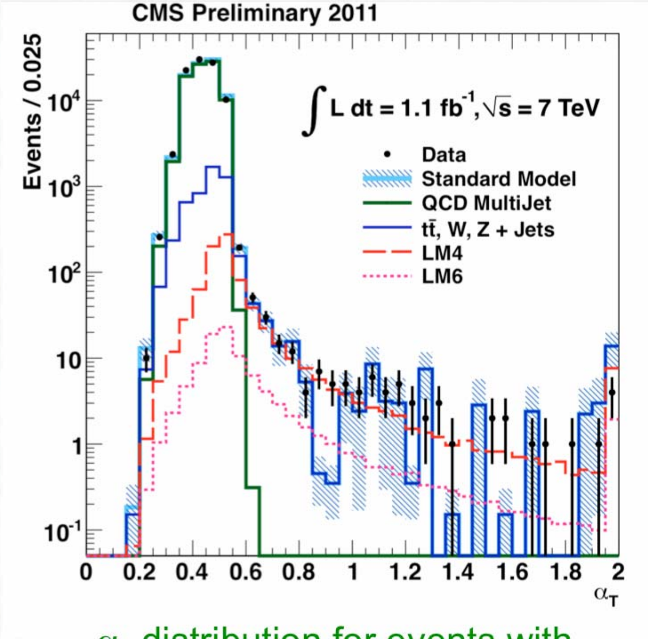
A display of the reconstructed event with the highest m_{eff} (1810 GeV) found in the ATLAS data sample. This event possesses five jets with p_T > 40 GeV (p_T = 528, 418, 233, 171 and 42 GeV respectively) and E_T^{miss} = 460 GeV.

SUSY searches in the CMS experiment

- Similar results have been obtained by the CMS experiment
- Data set corresponding to an integrated luminosity of 1.1 fb^{-1}
- Search for di-jet and multijet events accompanied by E_t^{miss}
- Use the kinematic variable α_T to discriminate between SUSY events and Standard Model background from multijet events

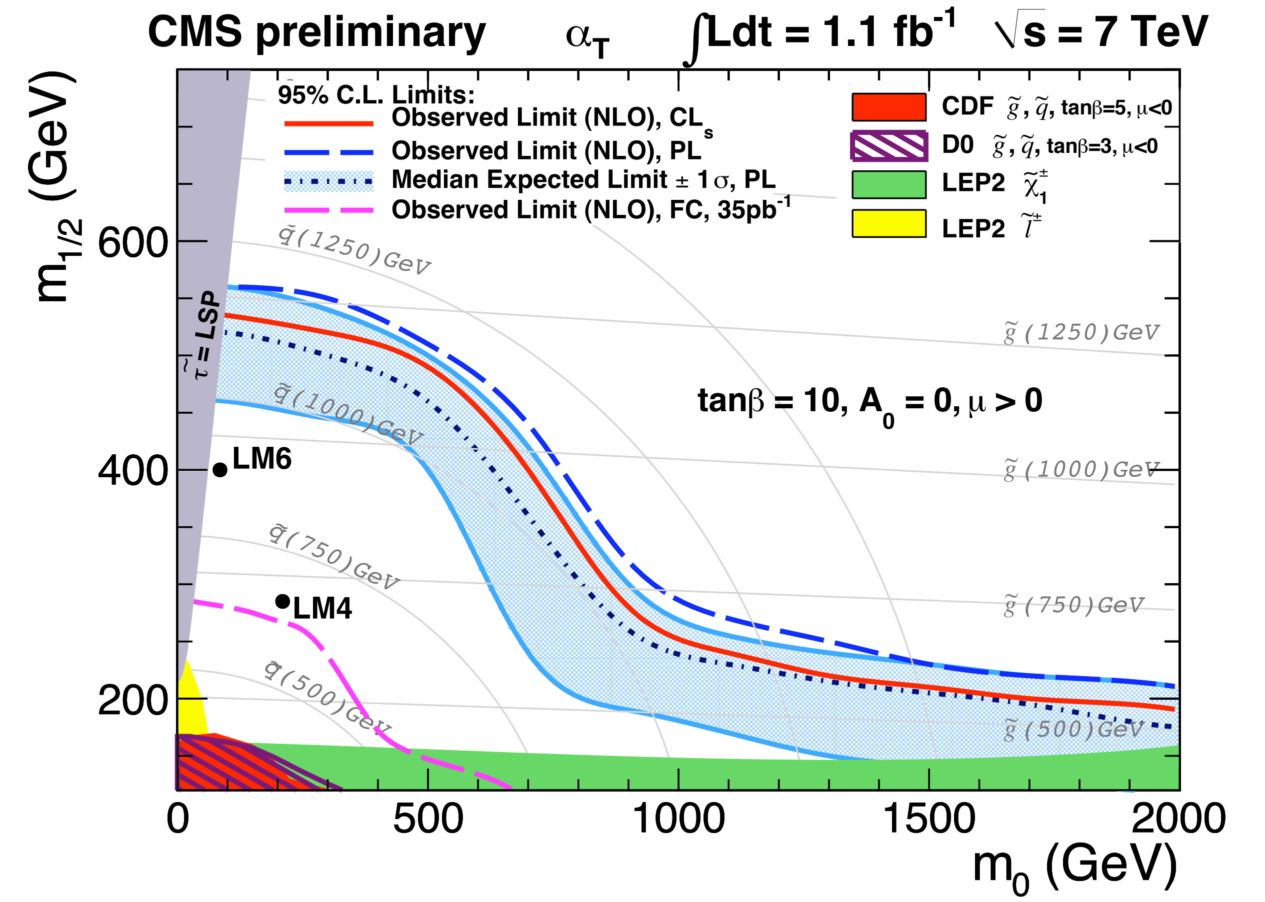
$$\alpha_T = \frac{E_T^{\mathrm{jet}_2}}{M_T} = \frac{E_T^{\mathrm{jet}_2}}{\sqrt{\left(\sum_{i=1}^{2} E_T^{\mathrm{jet}_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{\mathrm{jet}_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{\mathrm{jet}_i}\right)^2}}$$

- Shape analysis of α_T variable
- Background normalized in control regions from data



α_T distribution for events with H_T > 375 GeV and H_T^{miss} > 100 GeV

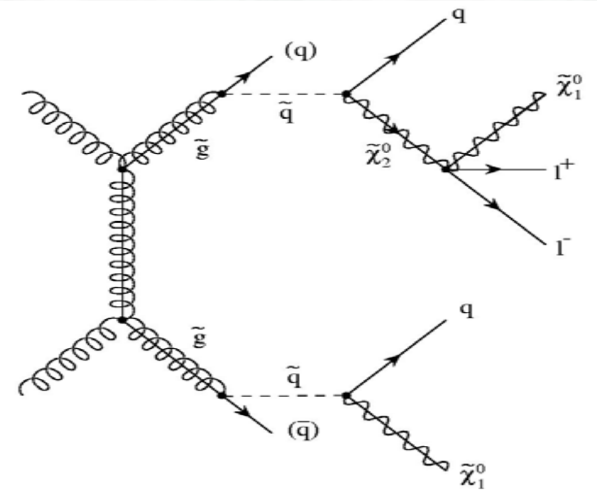
CMS exclusion limits in the cMSSM model



- Similar exclusion as from the ATLAS experiment:

  Squarks and gluinos with masses of 1.1 TeV can be excluded for m_0 < 500 GeV

Multijets + E_T^{miss} + 1 lepton

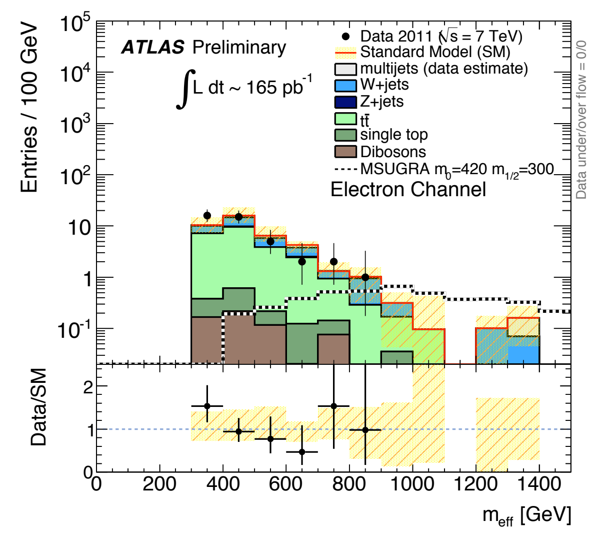


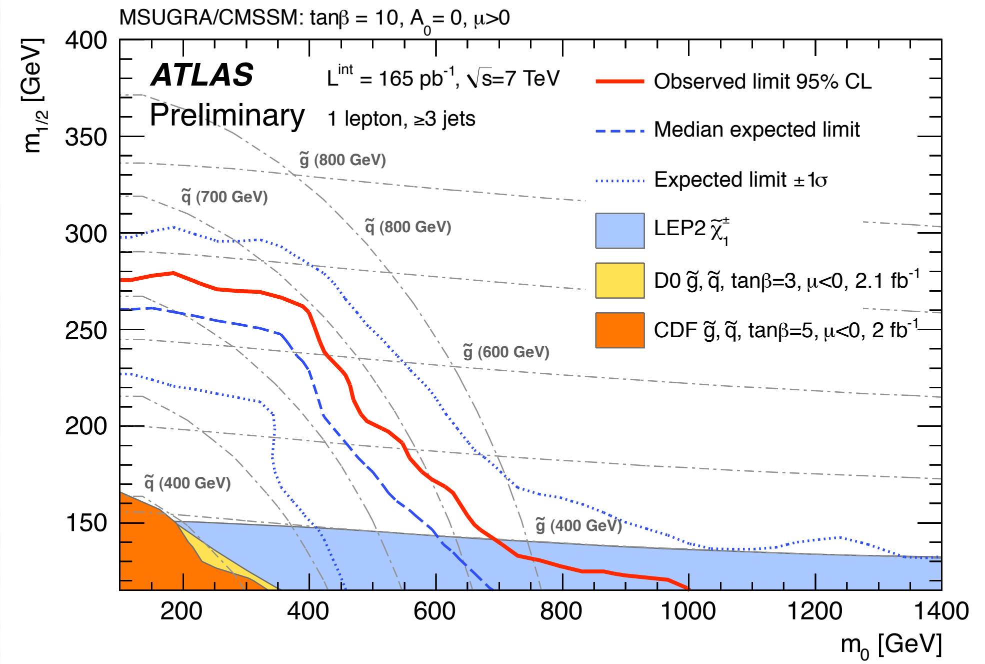
- Lepton might appear at the end of the SUSY decay cascade

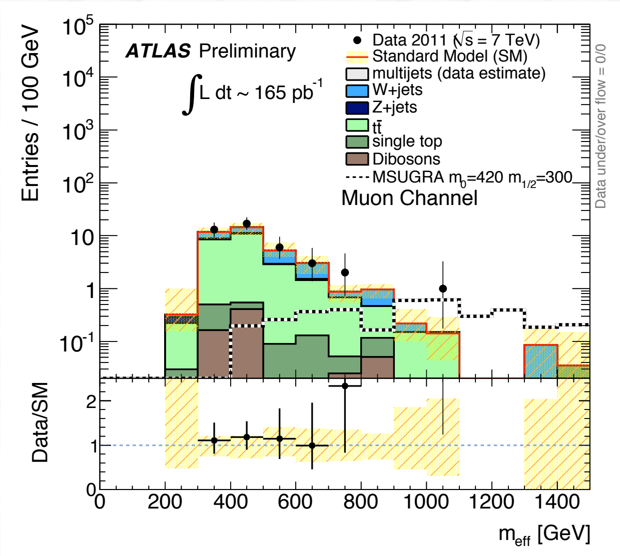
- Requiring a lepton changes the composition of the background from Standard Model processes significantly

  less QCD contributions,
  dominated by tt and W+jets,
  however, also less signal events

…additional potential: inclusive searches with leptons i.e. E_T^{miss}, jets + leptons (0.165 fb^{-1})





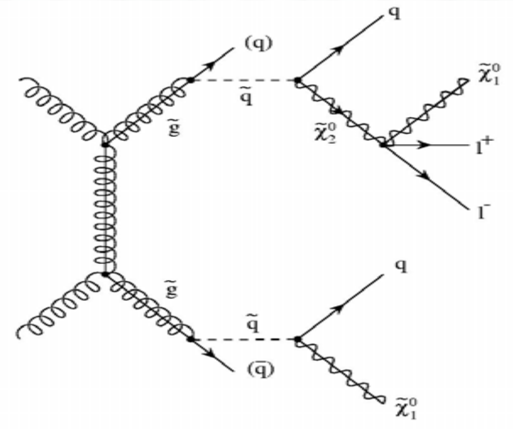


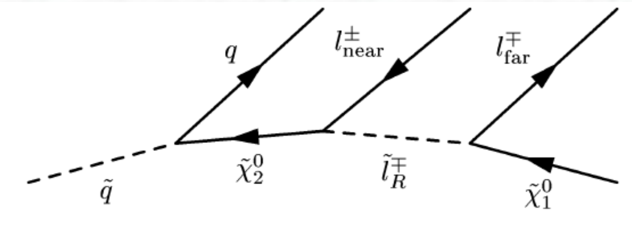
- Again: data are well described by contributions from Standard Model processes (background is dominated by tt events)

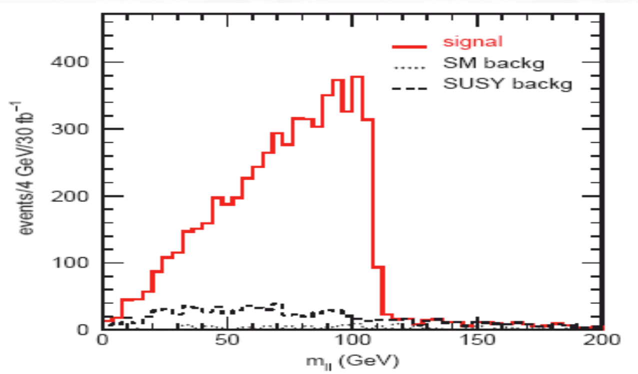
- Similar exclusions in the MSSM models (for comparable integrated luminosities)

E_T^{miss} + 2 leptons

(same sign or opposite sign)







- Leptons might appear from resonance decays

- more interesting: sensitive to cascade decays producing flavour correlated lepton pairs

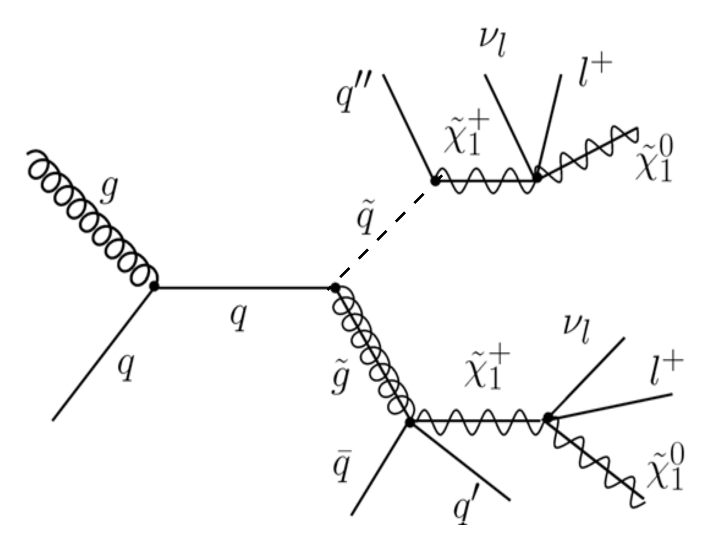
  → endpoint spectra contain information on mass differences of SUSY particles

  → important for SUSY parameter determination (as explained)

- Standard Model physics background expected to be small, in particular for like-sign lepton pairs

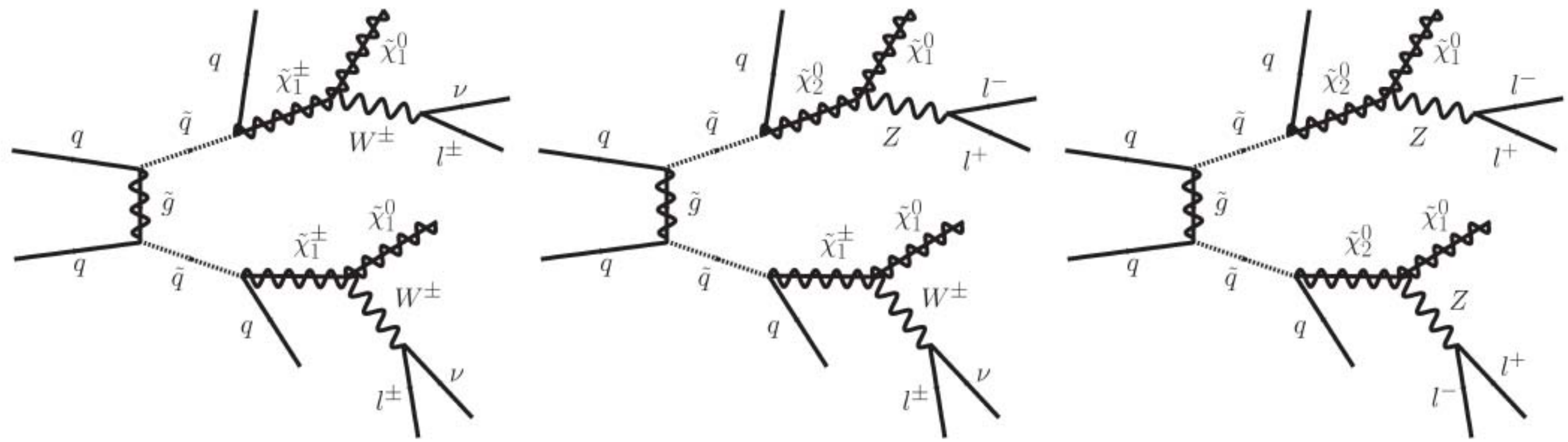
Like-sign di-leptons appear in many models of Physics Beyond the Standard Model:

- Supersymmetry
- Universal extra dimensions
- Heavy Majorana neutrinos
- Same sign top pair resonances



Backgrounds from Standard Model processes are in general small, contributions arise from:

- di-boson production (WZ)
- tt production, where a second lepton comes from semileptonic b-decays
- in general: non isolated leptons from heavy flavour decays
- fake leptons from misidentified jets



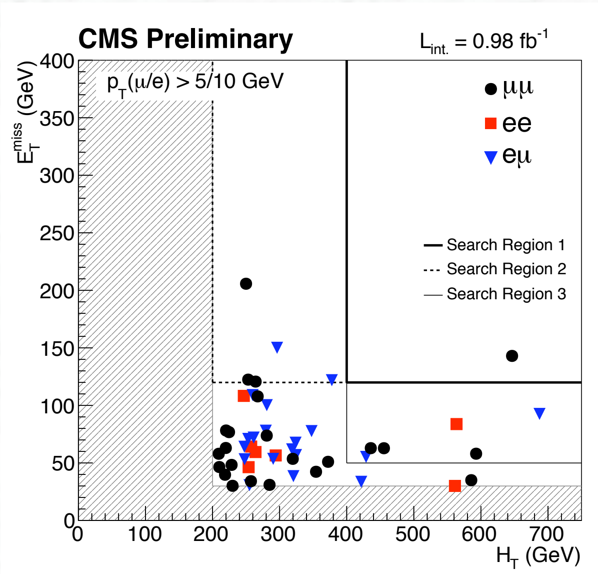
- Lepton p_T values in SUSY cascades might be low, depends on the mass differences of the SUSY particles involved → search for as low p_T leptons as possible

- Taus (3rd generation) may play a larger role, stau could be the lightest slepton → include leptons (hadronic decays in the search)

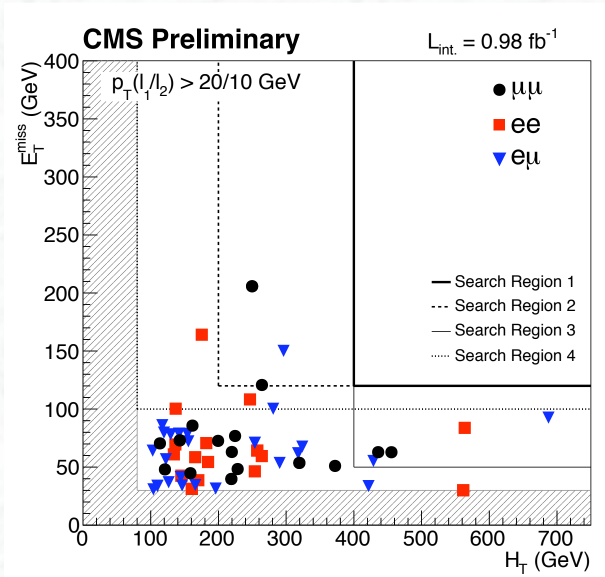
Di-lepton search in CMS

- Analysis based on data from 2011, L_{int} = 0.98 fb^{-1}

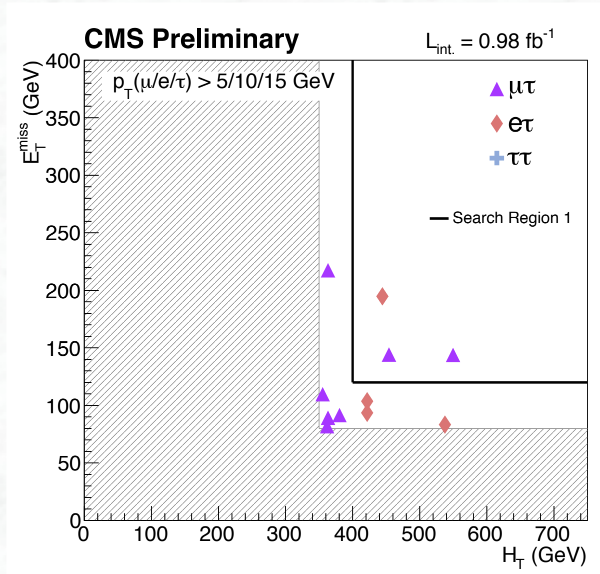
- Search for same-sign di-leptons (ee, eμ, $\mu\mu$, eτ, $\mu\tau$, $\tau\tau$) ($\tau = \tau_{had}$) accompanied by E_T^{miss} and jets in three different regions of phase space to increase sensitivity



Inclusive di-leptons



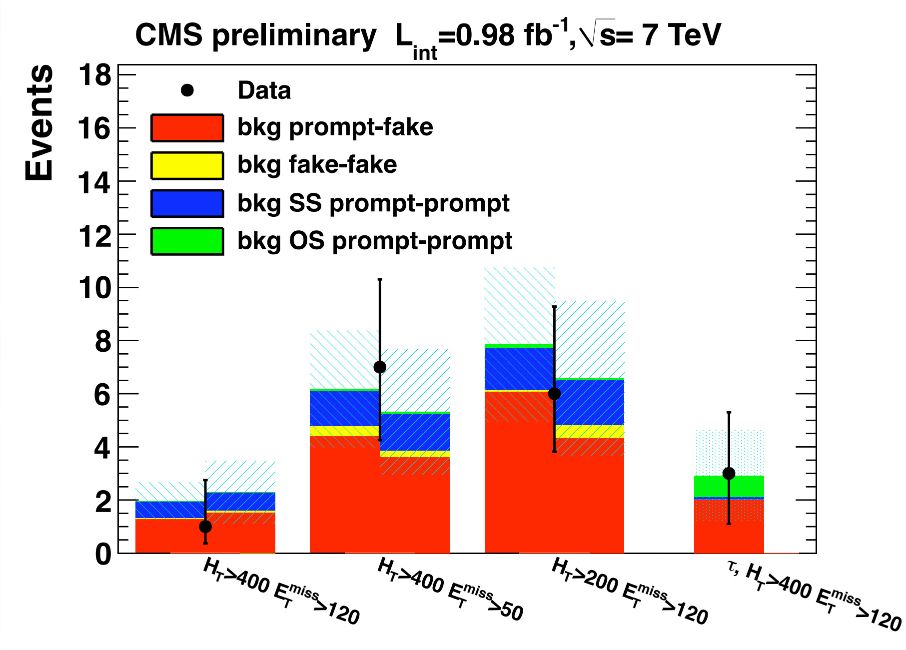
high p_T di-leptons



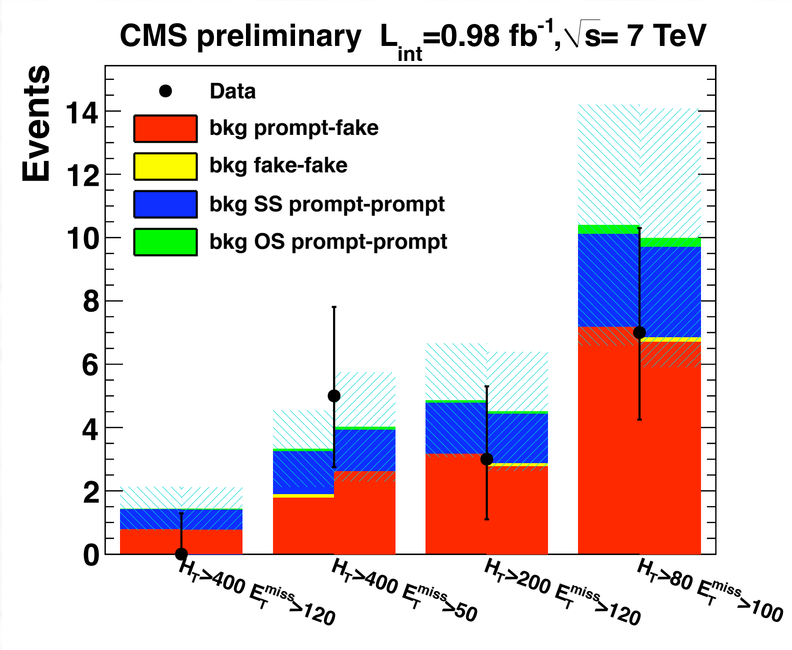
τ−di-leptons

- Discriminating variables to define signal regions: H_T and E_T^{miss}
- Low p_T lepton cuts compensated by higher cute on the hadronic activity (H_T)
- Three signal regions defined (see figure)

Comparison between data and expectations:



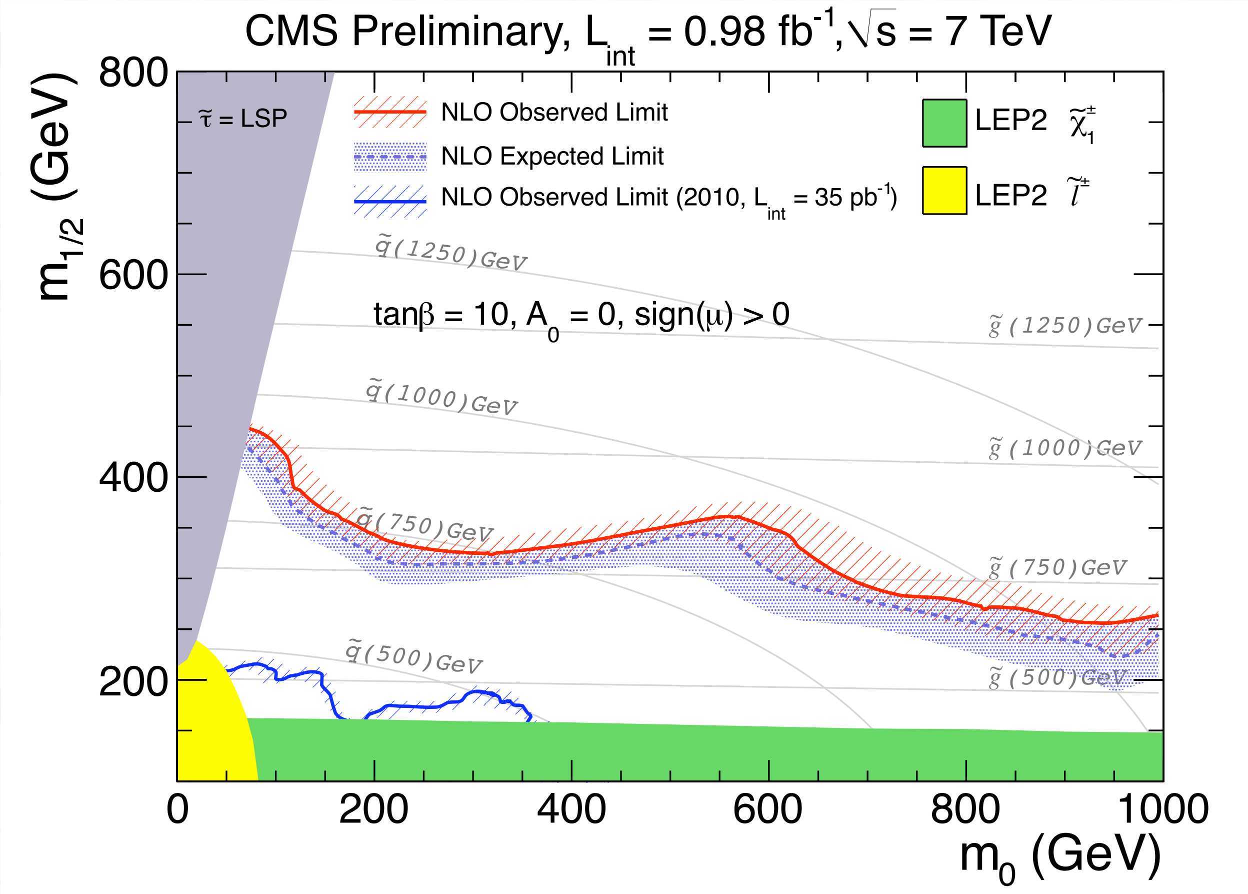
Inclusive and tau selection



high p_T di-lepton selection

- Good agreement beween data and expectations; no evidence for an excess
- Backgrounds are dominated by "fake" leptons;
  in addition, there is a component from charge mis-identification
- Estimates have large uncertainties (results from two methods shown)

Di-lepton based exclusion in the cMSSM model

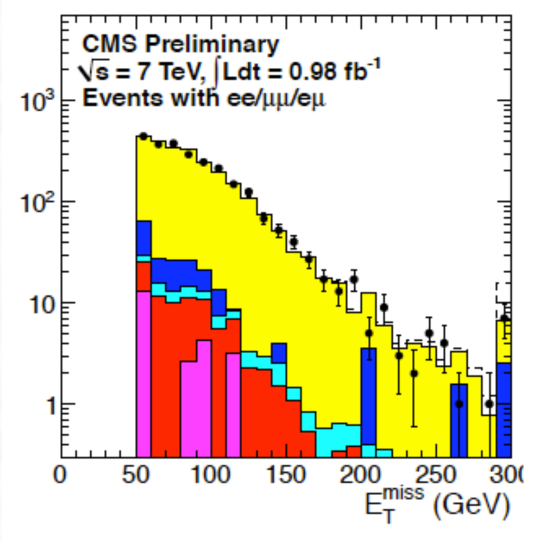


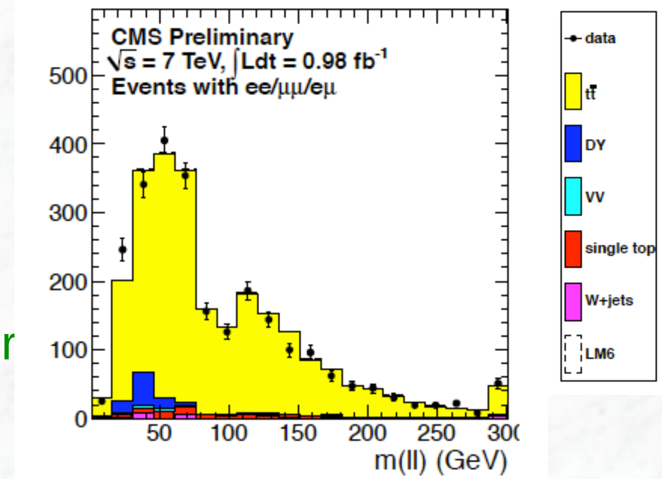
uncertainties on the cross sections (renormalization, factorization scale, pdfs) are indicated by the bands

- Exclusion extends to gluino masses of 825 GeV in the region $m_{squark} = m_{gluino}$
- For higher squark masses, gluinos with masses below 675 GeV are excluded

Search for anaomalies in opposite sign di-lepton events:

- Data from 2011, L_{int} = 0.98 fb^{-1}
- select events with two opposite sign, isolated leptons (ee, eμ, $\mu\mu$) with p_T > 20 / 10 GeV, $|\eta|$ < 2.5
- Resonance vetos: m_{ll} > 12 GeV,
  Z-veto: exclude 76 GeV < m_{ll} < 106 GeV
- At least two jets, with E_T > 30 GeV, H_T > 100 GeV
- E_T^{miss} > 50 GeV





Good agreement between data and expectations after these selection criteria are applied;
Selection criteria enrich tt contributions

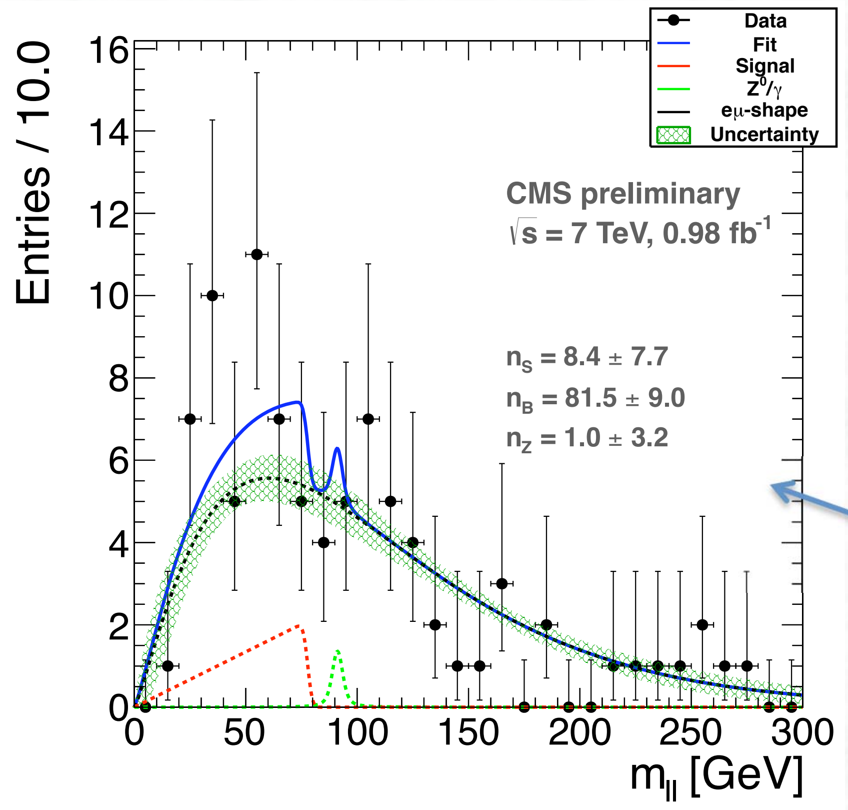
A first example to search for a characteristic edge in the opposite sign di-lepton mass spectra:

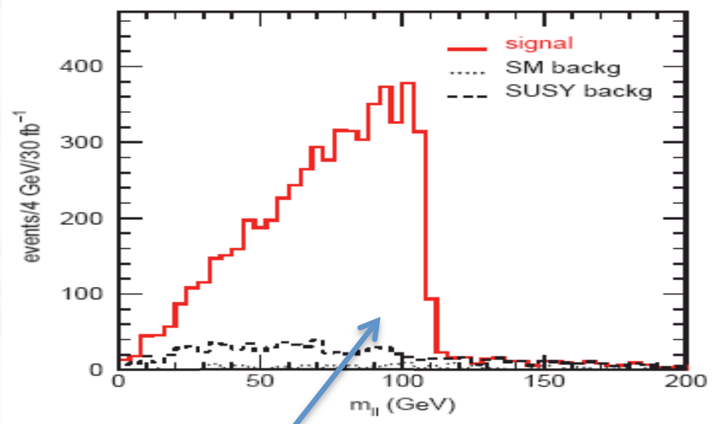
$$\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^{\pm}\ell^{\mp} \rightarrow \ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$$

$$M_{\ell^+\ell^-}^{max} = \frac{\sqrt{(m_{\chi_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\chi_1^0}^2)}}{m_{\tilde{\ell}}}$$

- Remove Z veto cut

- Tighter E_T^{miss} cut: $E_T^{miss} > 100$ GeV
- Signal region: $H_T > 300$ GeV
- Control region: $100 < H_T < 300$ GeV



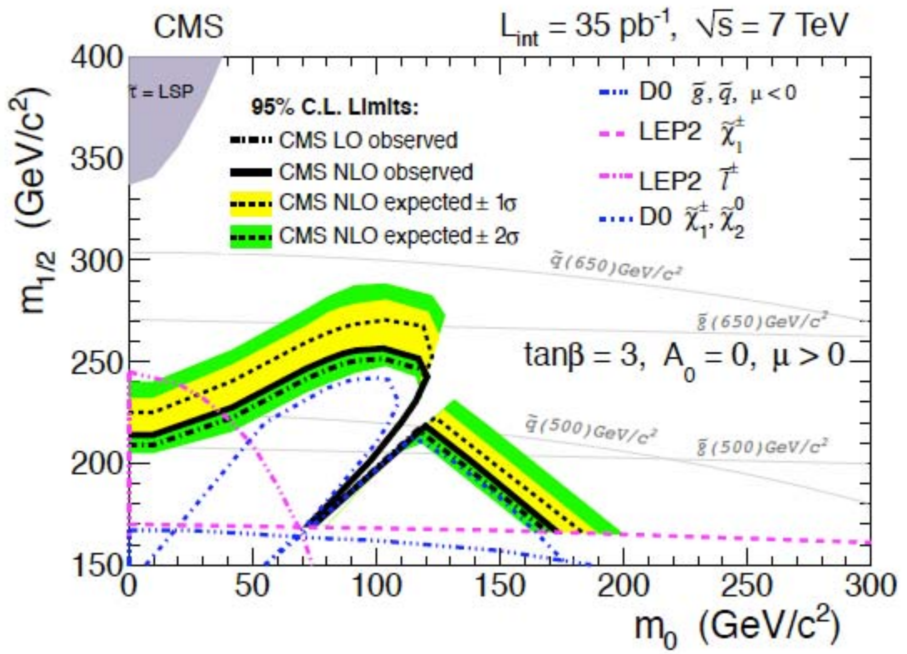


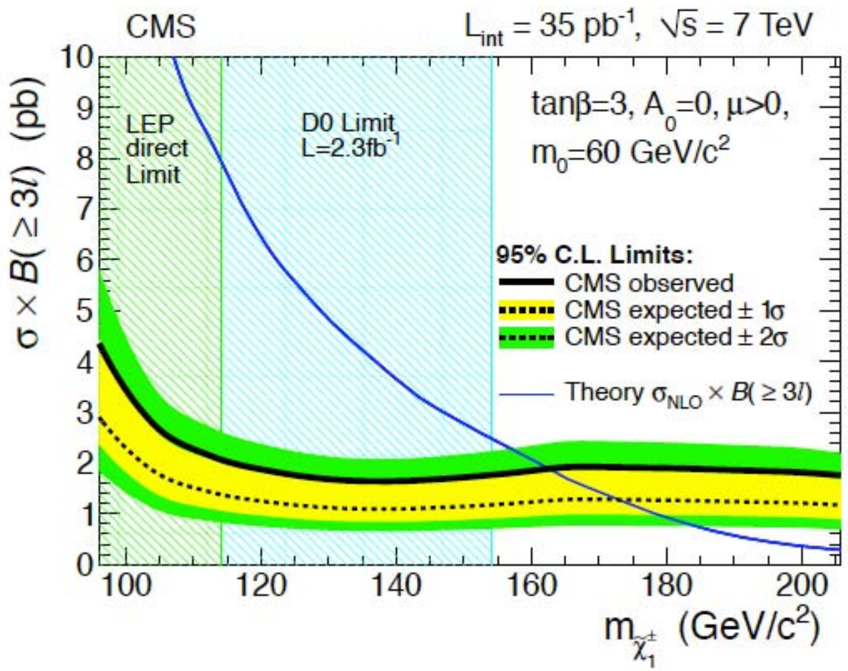
MC simulation

CMS Data 2011

No evidence for a characteristic di-lepton edge in the data

Multi-lepton (> 3) search in CMS

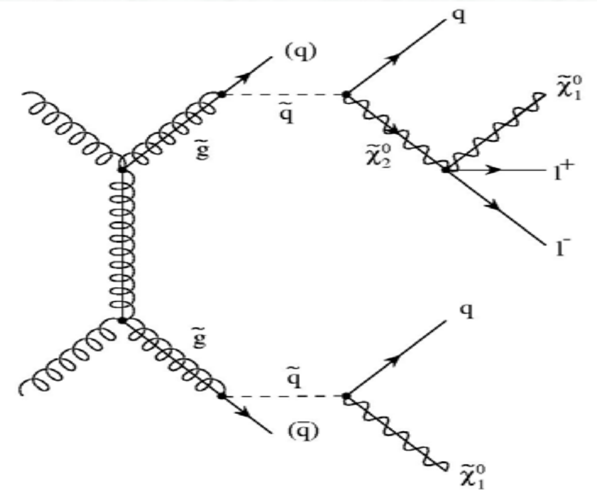




- Multi-leptons are produced via associated production of charginos and neutralinos (like at Tevatron, see above)

- First limits on chargino mass from the LHC;
  Limits extracted with 2010 data are already beyond the Tevatron reach

E_T^{miss} + 0/1 leptons + b jets



- There might be large mixing effects, between scalar partners of left- and right-handed quarks

- proportional to the corresponding SM fermion masses, therefore important in the third generation
  sbottom and stop might be the lightest squarks

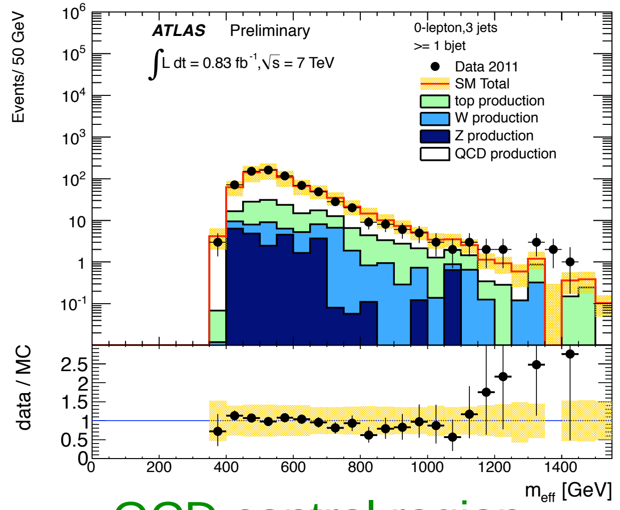
  → b quarks appear in their decays

  production e.g. via gluino-pair production with subsequent decays:

$$\tilde{g} \rightarrow \tilde{b}_1 b \text{ or } \tilde{g} \rightarrow \tilde{t}_1 t$$

ATLAS search for events with at least one b-jet, 0 lepton and E_T^{miss} :

- Data from 2011, L_{int} = 0.83 fb^{-1}
- Select events with at least three jets with, p_{T1} > 130 GeV, no identified leptons (e,μ)
- E_T^{miss} > 50 GeV
- Require one or two b-tagged jets

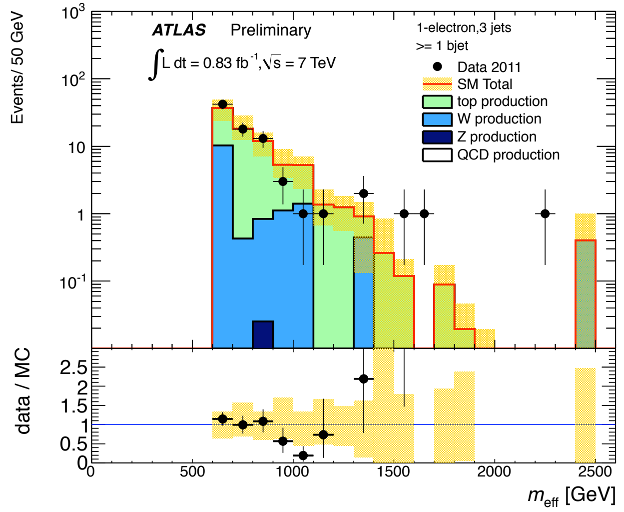


QCD control region

- Background determined / checked in control regions

(i) events with 1 lepton (to constrain tt background)

(ii) events with reversed Δϕ (jet,E_T^{miss}) cut (to constrain QCD multijet background)

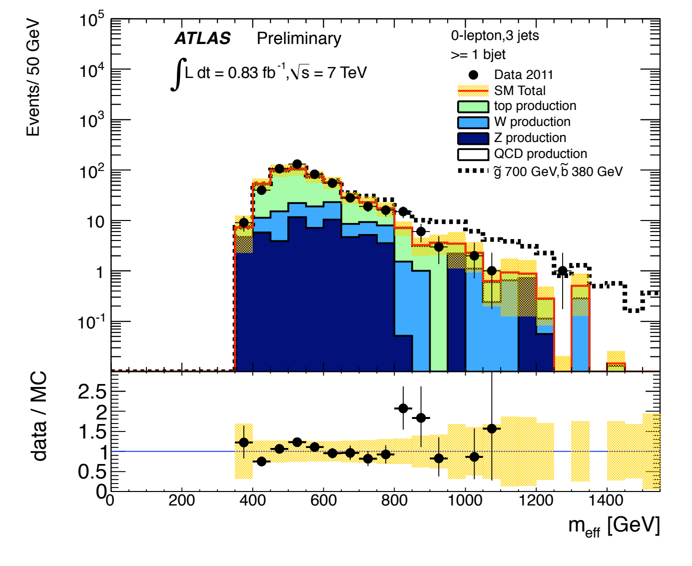


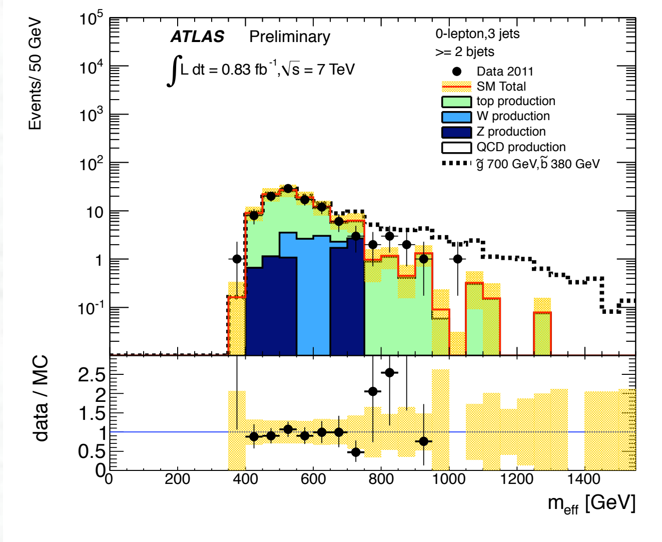
tt control region

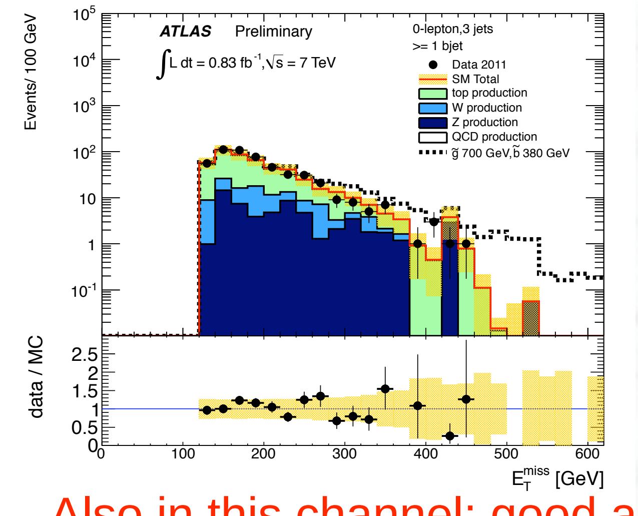
Comparison of data and expectations in the signal region:

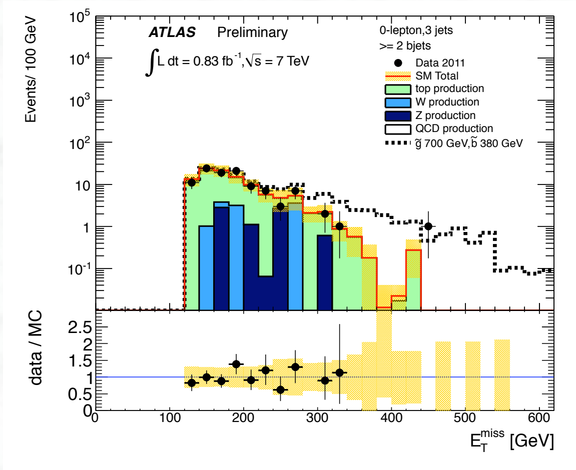
events with 1 b-tagged jet

events with 2 b-tagged jets



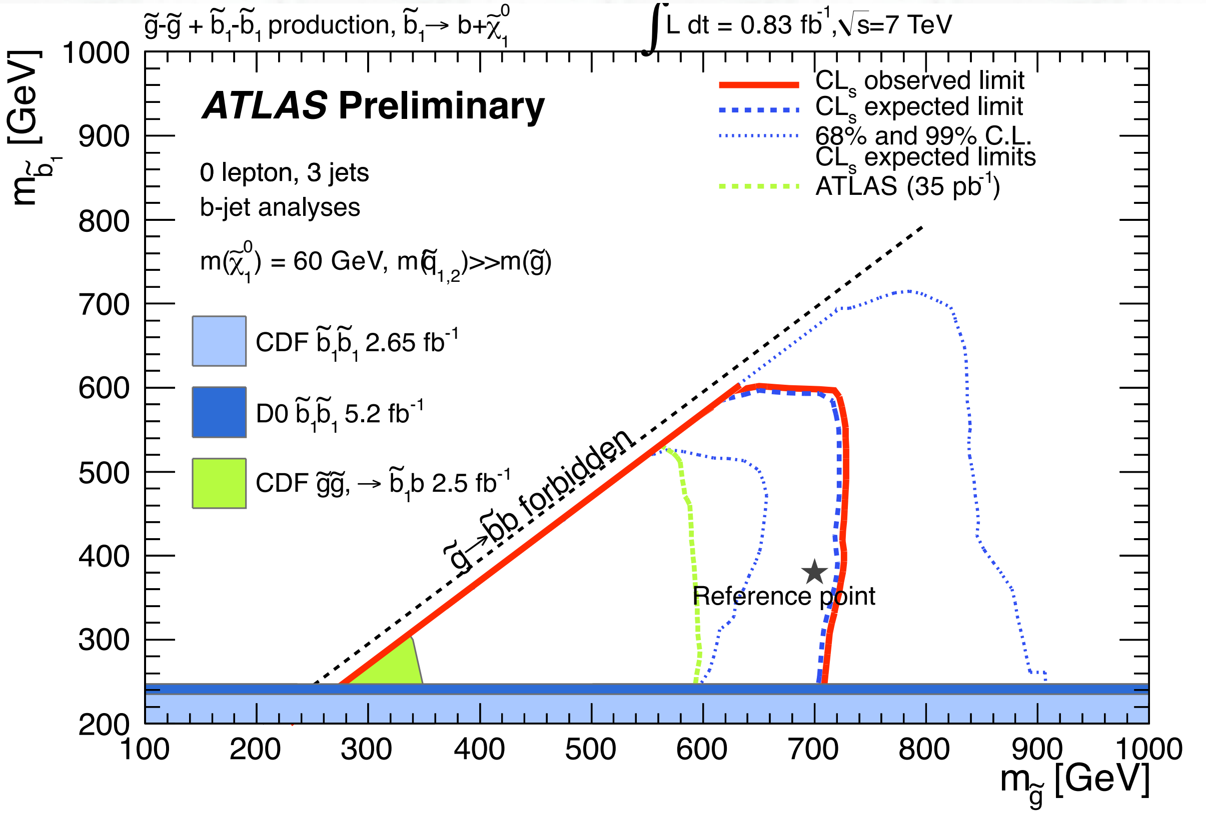






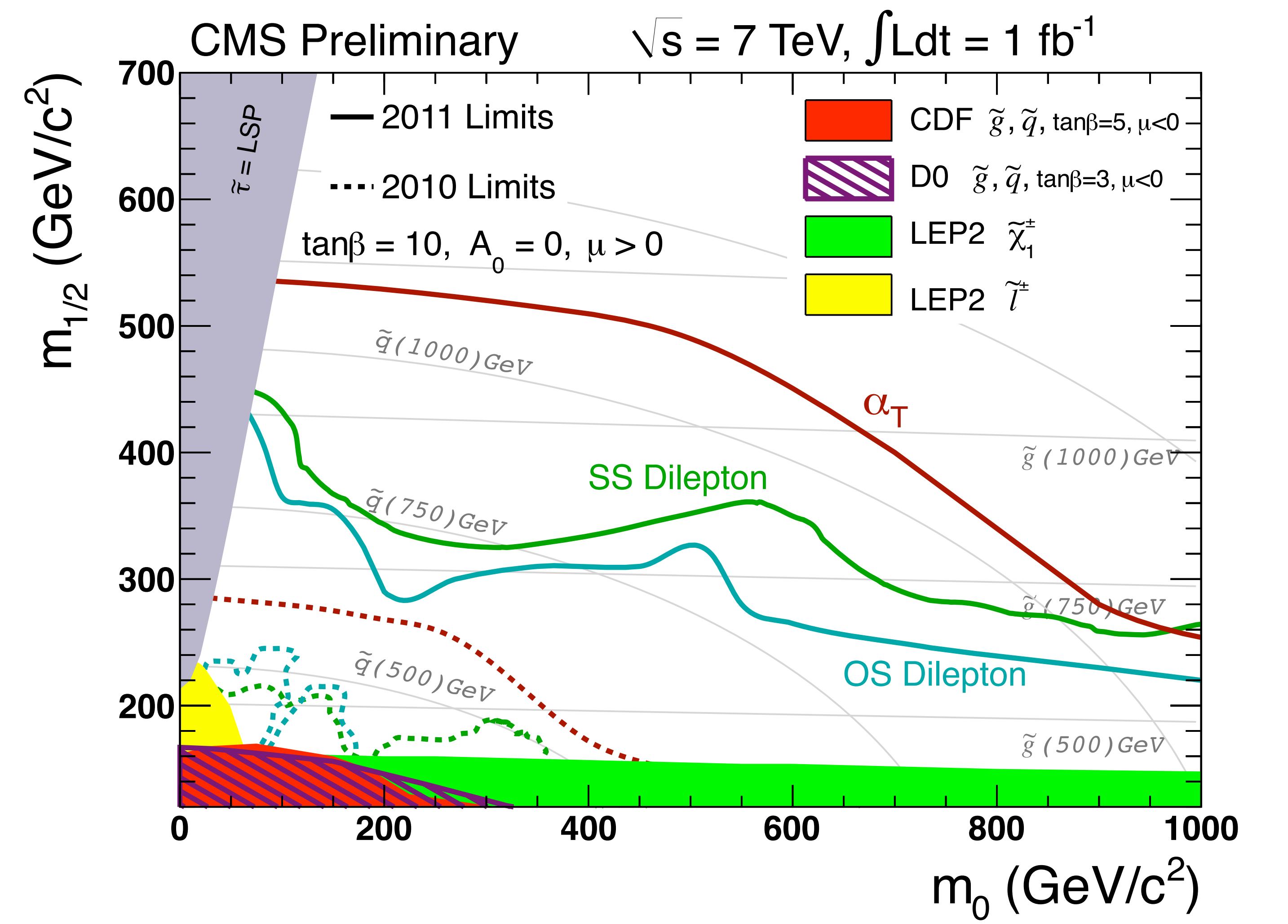
Also in this channel: good agreement between data and expectations from Standard Model

Exclusion limits in the ($m_{sbottom}$-m_{gluino})-plane, for the hypothesis that the lightest squark (sbottom1) is produced via gluino-mediated production or direct pair production and decays 100% via $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$



- Gluino masses below 720 GeV for sbottom masses of ~600 GeV

Summary of R-parity conserving SUSY searches in CMS



Intermediate Summary:

- ATLAS and CMS experiments have very efficiently analyzed their data;
- Results already available for data corresponding to an integrated luminosity of ~1 fb^{-1}
- So far: search for R-parity conserving SUSY scenarios not successful:

  - Many final states and topologies were explored;
  - Data are consistent with expectations from Standard Model processes
  - No evidence for SUSY up to nearly the 1 TeV scale

→ What about other SUSY scenarios ?

(i) Change SUSY breaking scenario

e.g. GMSB
- search for photons
- search for long-lived particles

(i) Give up R-parity conservation

- Abandon pair production and the E_T^{miss} signature

A few selected examples of such studies are shown in the following

Search for Gauge Mediated SUSY breaking scenarios (GMSB)

- In Gauge mediated SUSY breaking (GMSB) models, SUSY breaking occurs at energy scales much smaller than the Planck scale, breaking linked to gauge interactions

- The gravitino is the LSP, escapes detection → E_T^{miss} signature is kept

- Phenomenology is determined by the NLSP (next-to-lightest SUSY particle);

  In many scenarios the NLSP are the superpartners of the $SU(2)_L$ gauge fields, with small mass splittings between the charged and neutral winos

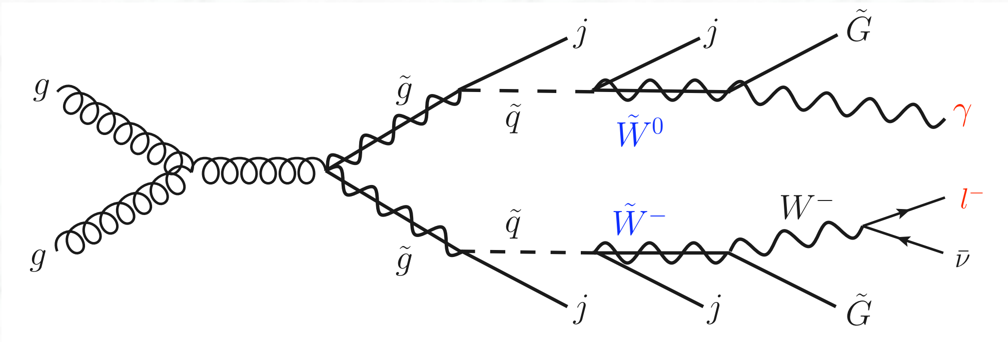
  - Decays scenarios: $\tilde{W} \to \gamma \tilde{G}$ $\quad$ $\tilde{W}^+ \to W^+ \tilde{G}$

  - Also χ_1^0 can be the NLSP with decays: $\chi_1^0 \to \gamma \tilde{G}$

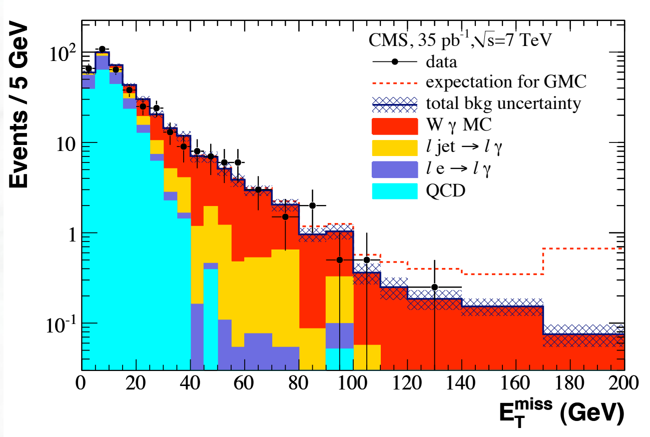
  → expect / search for events with Photons, Leptons and E_T^{miss}

- In GMSB models sleptons, squarks and gluinos might have long lifetimes

CMS search for lepton (e,μ) + photon + E_T^{miss}:

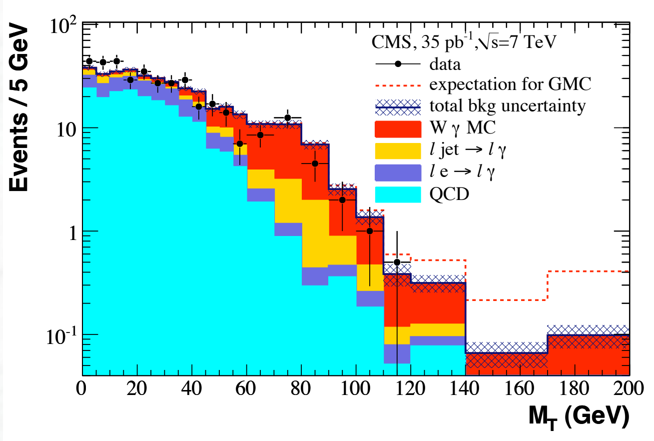


- Data from 2010, L_{int} = 0.035 fb^{-1}



- Select events with:
  - at least one lepton with p_T > 20 GeV and η < 2.1
  - one photon with p_T > 30 GeV and η < 1.44

- E_T^{miss} > 100 GeV



- Good agreement between data and expectations (see E_T^{miss} and M_T distributions)
- Wγ production is the dominant background

ATLAS search for $\gamma\gamma$ + E_T^{miss}:

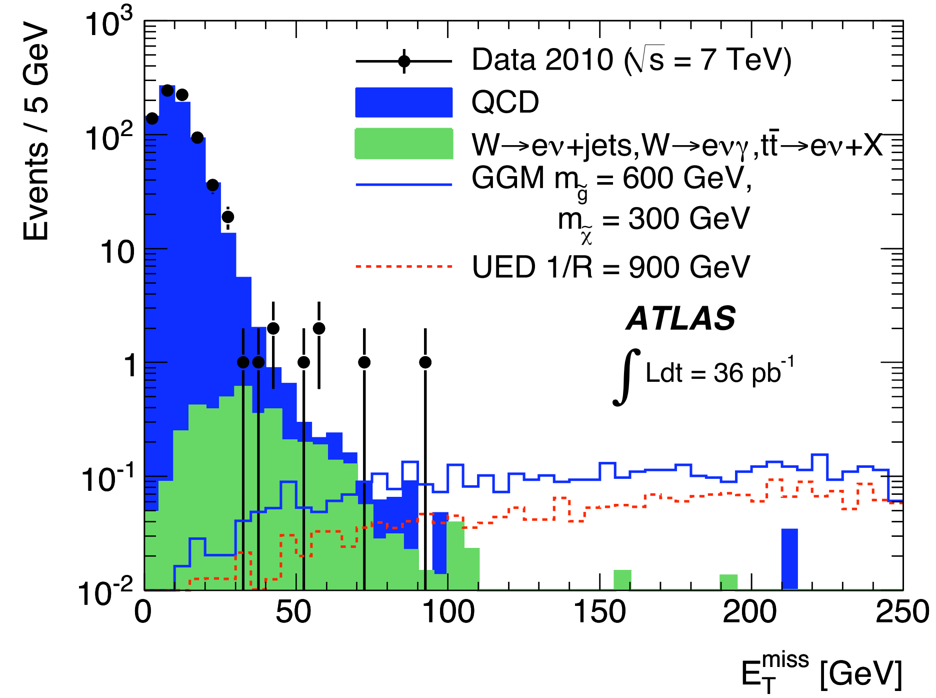
- Data from 2010, L_{int} = 0.035 fb^{-1}

- Select events with:
  - two photons with p_T > 30/20 GeV and η < 2.47
  - isolation criteria

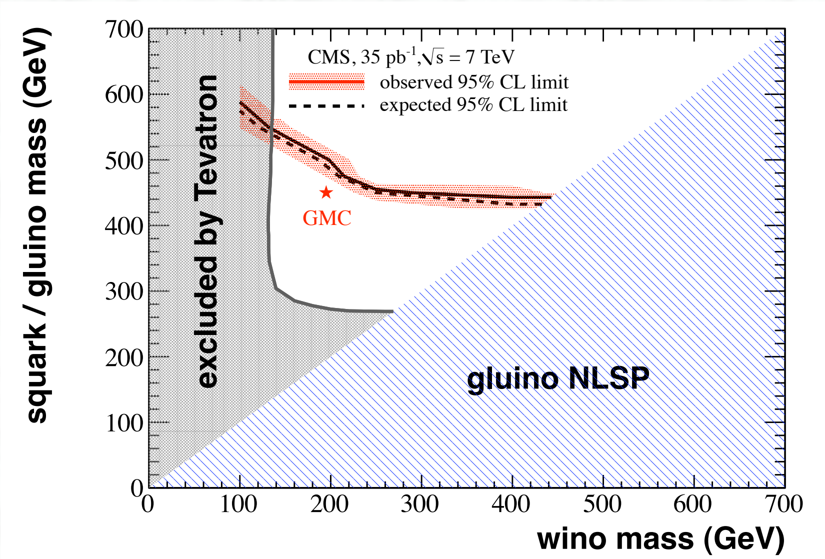
- Signal region defined for E_T^{miss} > 125 GeV

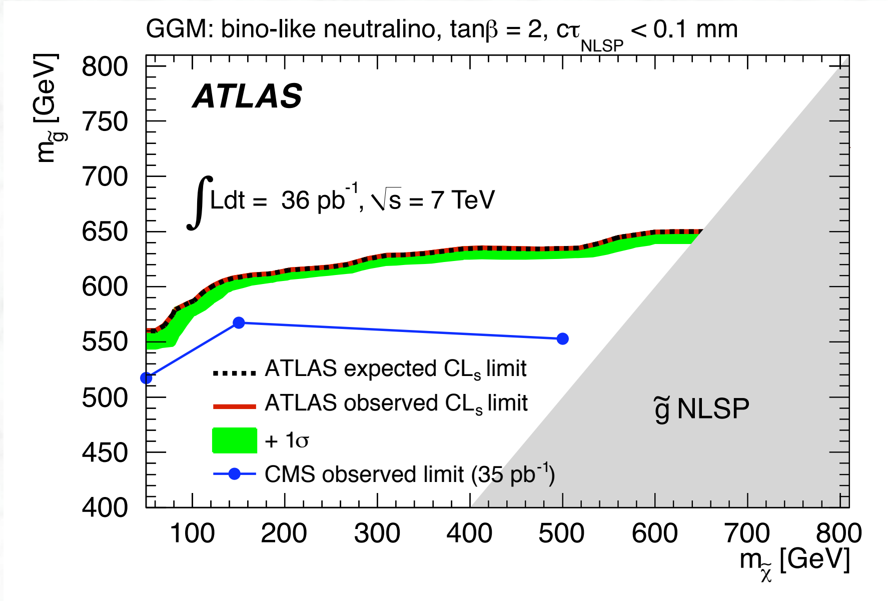
- Good agreement between data and expectations (see E_T^{miss} distributions)

- QCD fake photons and W production constitute major backgrounds



95% C.L. Excluced regions





Search for long-lived particles (LLP)

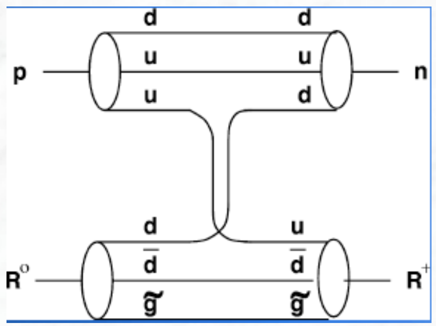
- SUSY models allow as well for metastable sleptons, squarks and gauginos
- A produced heavy long-lived particle would travel with a velocity significantly lower than the speed of light

  particle mass can be determined via the measurement of the momentum and β (velocity, from time of flight) via the relation

$$m = \frac{p}{\beta\gamma}$$

- Long-lived sleptons would interact like heavy muons, releasing energy by ionization as they pass through the detector
- Coloured LLPs (squarks and gluinos) would hadronize, forming so-called R-hadrons, bound states composed of the LLP and light quarks and gluons

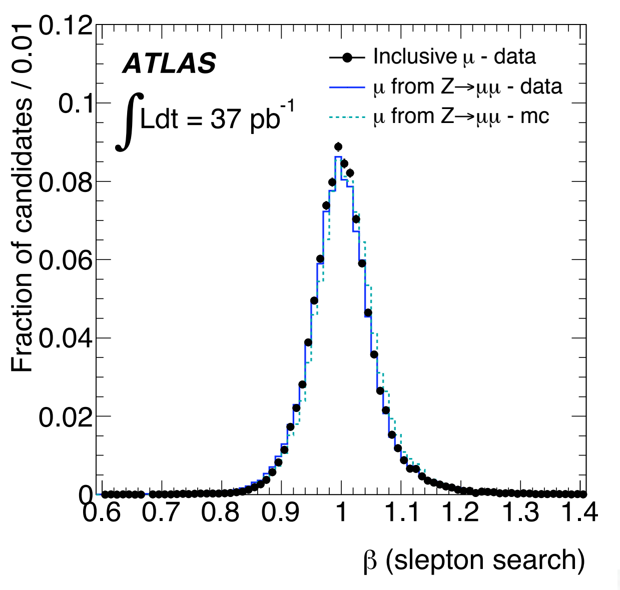
  They can emerge as neutral states from the pp collision and become charged by interactions with the detector material (calorimeters), arriving as charge particle in the muon spectrometer

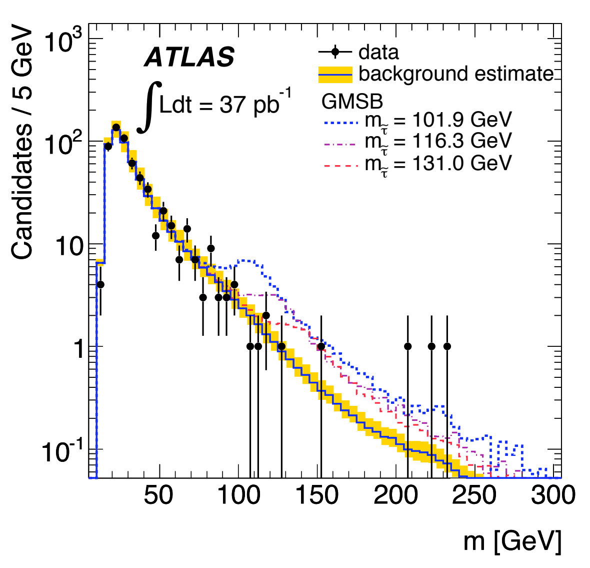


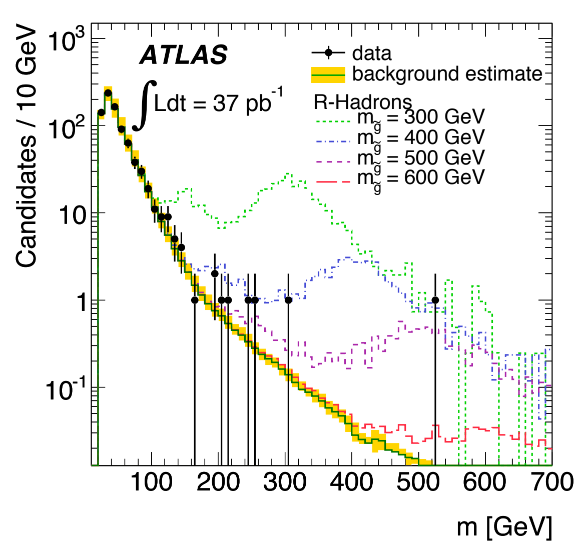
ATLAS search for long-lived sleptons and R-hadrons:

- Use muon spectrometer to reconstruct slow “muon-like” particles (special adapted reconstruction package)
  → β and momentum measurement

- Analysis based on 2010 data, 0.037 fb^{-1}



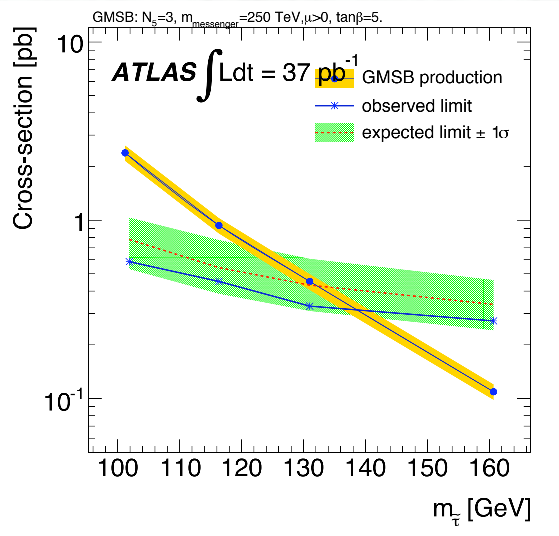


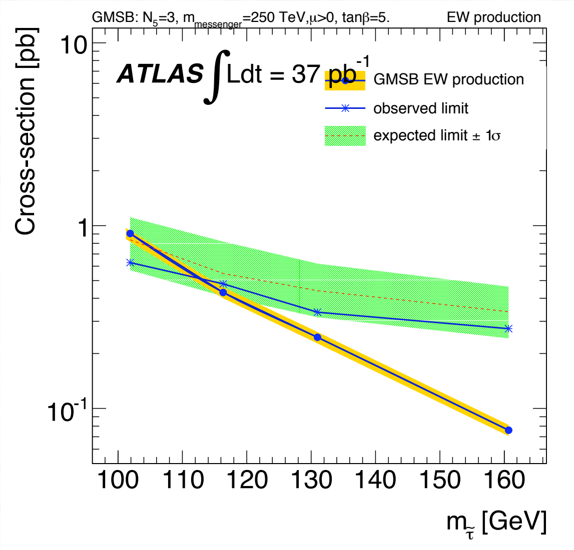


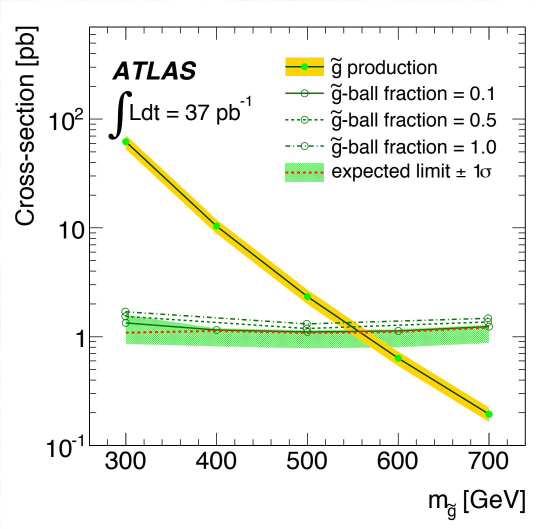
- The reconstructed β distribution agrees with the muon hypothesis

- The reconstructed mass distributions show no evidence for an excess caused by a long-lived particle

→ limits on the production cross sections of GMSB sleptons and gluino-R-hadrons have been set:
(model parameters: $N_5 = 3$, $m_{messenger} = 250$ TeV, sign $\mu = 1$, $\tan\beta = 5$)







These cross sections can be interpreted in GMSB models as mass limits;
Details depends on the model parameters

If electroweak production of sleptons is assumed, mass limit is at 110 GeV
(previous limits on stable sleptons are all below 100 GeV)

First Searches for R-parity violating SUSY

$$W_{\mathrm{RPV}} = \sum_i \mu_i L_i H_u + \sum_{i,j,k} \left(\frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c \right)$$

$$i, j, k = (1, 2, 3)$$

Label quark and lepton generations of chiral superfields

$$\left.\begin{matrix} \lambda_{ijk} = -\lambda_{jik} \\ \lambda'_{ijk} \end{matrix}\right\}$$ Responsible for lepton number violation

$$\lambda''_{ijk} = -\lambda''_{ikj} \;\}$$ Responsible for baryon number violation

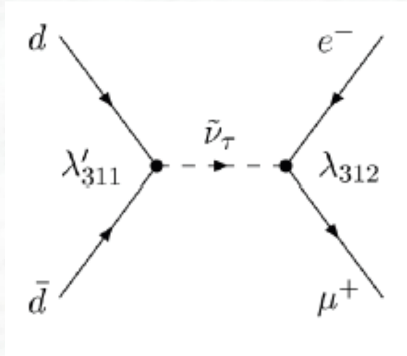
- Lepton and/or baryon number violated
  however: existing constraints from low-energy experiments must be fulfilled

- The LSP is non-stable and decays
  → the missing energy signature is lost
  → rich phenomenology, with multi-lepton final states, low E_T^{miss}

- R-parity violating SUSY breaks the SUSY-Dark Matter connection

ATLAS search for an eμ-resonance

- With a non-vanishing RPV λ' coupling a sneutrino or Z' can be produced at the LHC and it can decay into an e-μ final state

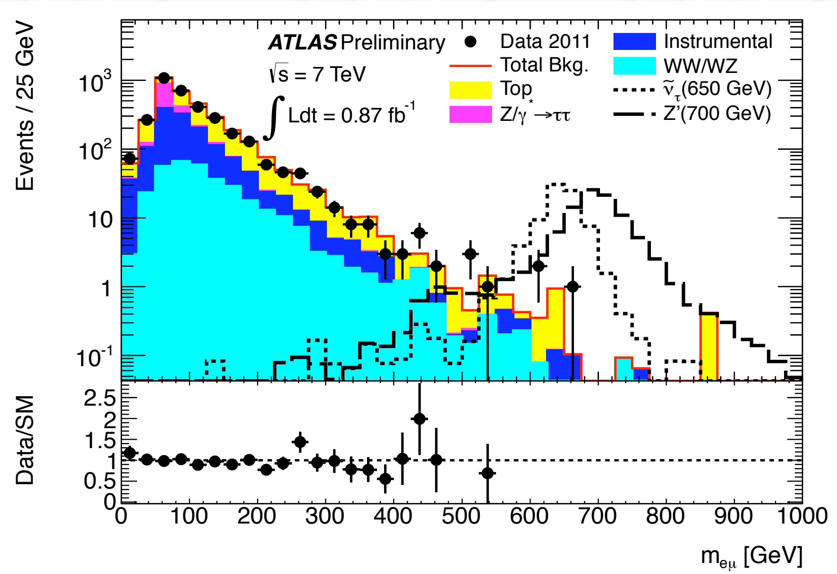


- ATLAS analysis, based on 2011 data, $L_{int} = 0.87\ fb^{-1}$

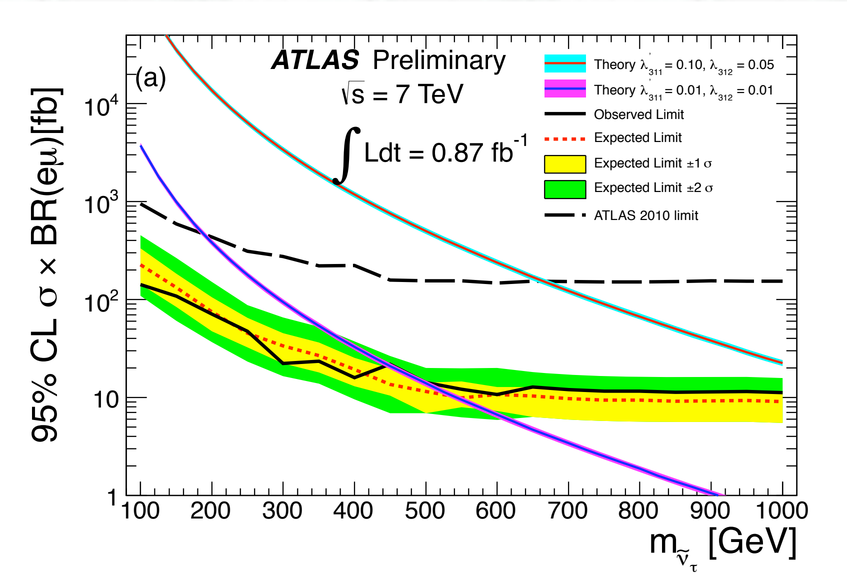
- Require both an isolated electron and an isolated muon with $p_T > 20$ GeV, within lepton acceptance

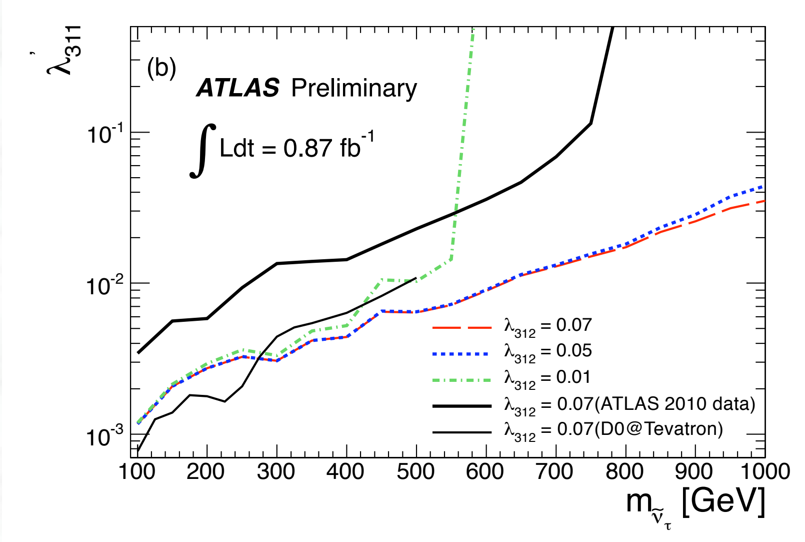
- e-μ invariant mass spectrum shows no evidence for a resonance structure (main physics backgrounds: tt and Z→ ττ)

Process	Number of events
$Z/\gamma^* \to \tau\tau$	614 ± 53
$t\bar{t}$	1281 ± 168
WW	318 ± 24
Single top	125 ± 17
WZ	18.2 ± 1.9
$W/Z + \gamma$	67 ± 11
Jet instrumental background	984 ± 105
Total background	3408 ± 230
Data	3338



95% C.L. limits on the cross section times BR as function on the sneutrino mass and limits on the RPV coupling λ_{311} (for various λ_{312} values)





- Only τ-sneutrinos considered, given the already stringent limits on the electron and muon sneutrinos
- All RPV couplings, except λ_{311} and λ_{312} are fixed to zero and the τ-sneutrino is assumed to be the lightest SUSY particle

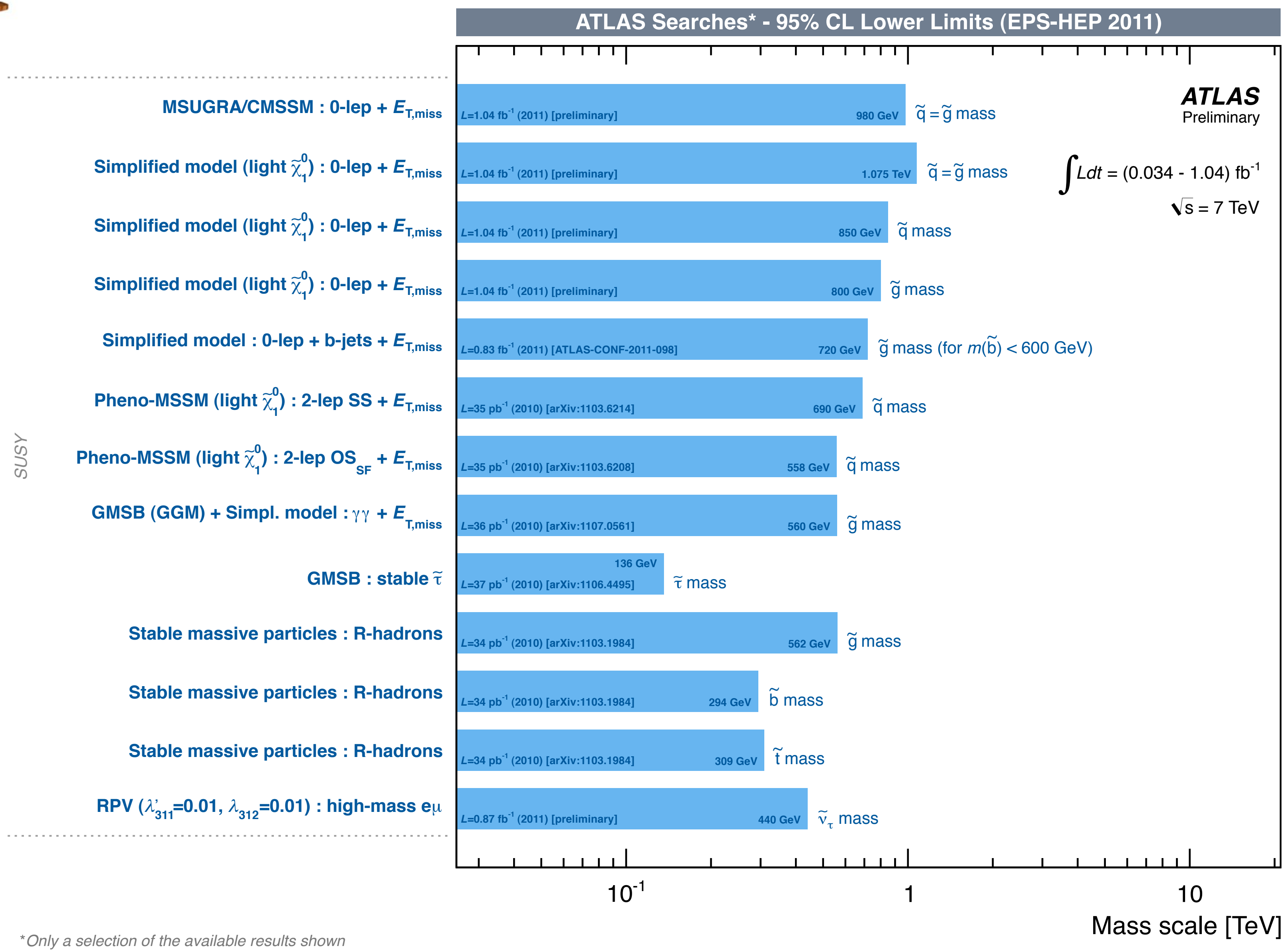
Summary on SUSY searches:

- ATLAS and CMS experiments have very efficiently analyzed their data;
- Results already available for data corresponding to an integrated luminosity of ~1 fb^{-1}
- So far: search for SUSY scenarios not successful:

  - Many final states and topologies were explored;
  - Data are consistent with expectations from Standard Model processes;
  - No evidence for SUSY up to nearly the 1 TeV scale

  → ATLAS summary plot

Summary of R-parity conserving SUSY searches in ATLAS



*Only a selection of the available results shown

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- SUSY doesn't seem to show up at the $<$ 1TeV scale
- Frustration level increased
- Is there a SUSY future at the LHC ?

Changing Prospects for Higgs and SUSY ?

1985: No – Lose theorem
LHC will discover a Higgs boson and/or a Supersymmetric World

1995: Maybe SUSY will not be realized in its minimal version ….
(maybe there is NMSSM, …..)

…. but we believe in SUSY (see e.g. J. Ellis, hep-ph 9503426)

negligible in this range. Similar sensitivity is to be expected in the CMS experiment [14]. Thus essentially all the parameter space of the MSSM allowed by naturalness arguments will be covered. If the LHC does not discover supersymmetry, we theorists will have to eat our collective hat.

2006: No discoveries at LEP-II and Tevatron (so far), Standard Model still rules !
Maybe SUSY is not realized as a *Low Energy SUSY* …..

"The SUSY-train is already a bit late….." (G. Altarelli)

New models: extra space time dimensions, …… including dark Higgs scenarios !
(e.g. J.van der Bij et al., Higgs boson coupled to a higher dimensional singlet scalar, hep-ph/0605008)

in the range $s^{1/2} > 100\,\mathrm{GeV}$. The data show a slight preference for a five-dimensional over a six-dimensional field. This Higgs boson cannot be seen at the LHC, but can be studied at the ILC.

LHC reach: or where can we go with √s = 14 TeV

present ATLAS and CMS limits